Application-Specific Research in Nanotechnology

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For:
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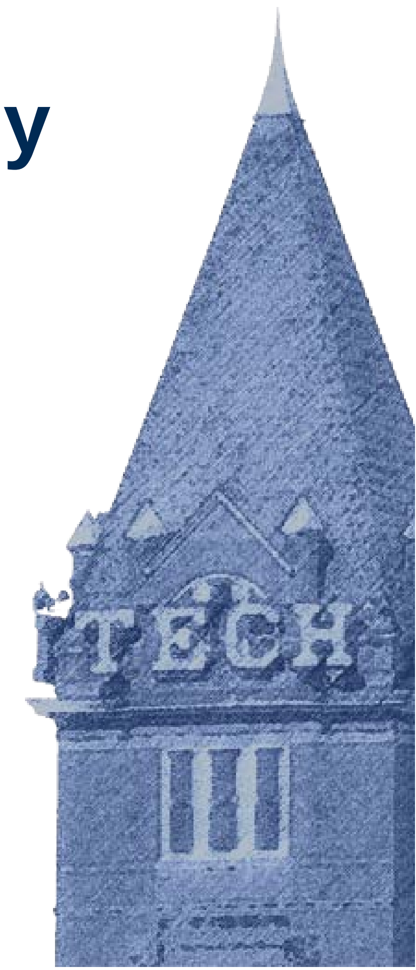
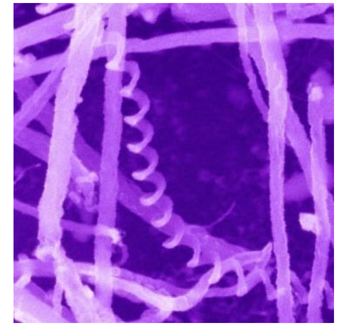
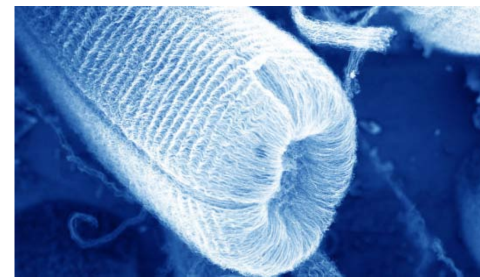
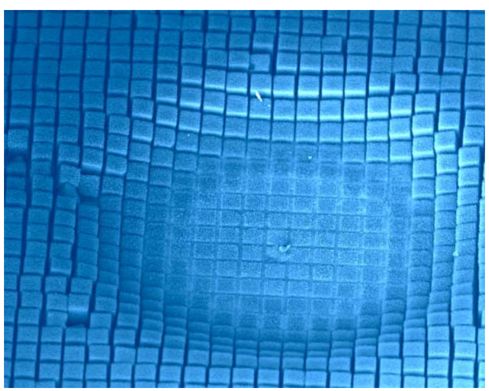


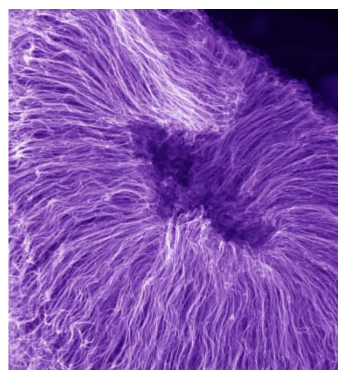
Overview

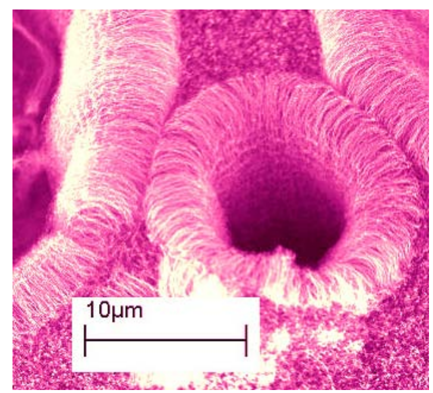


- Motivation, Background & Equipment
- Selected Projects
- Q/A



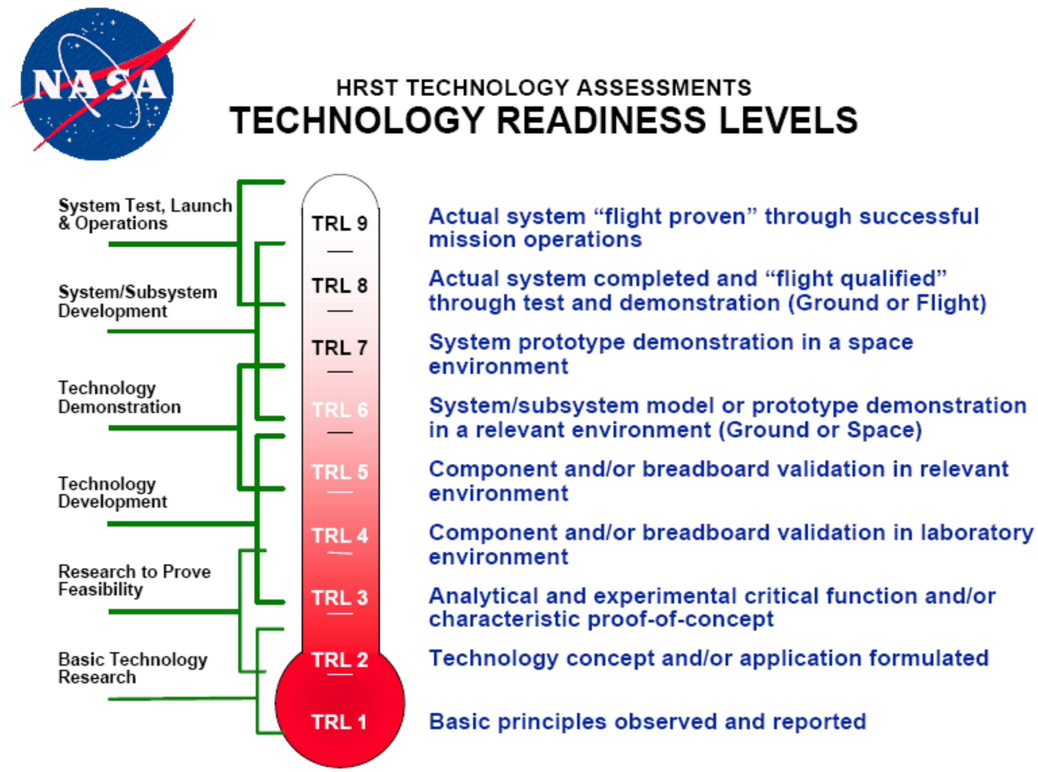






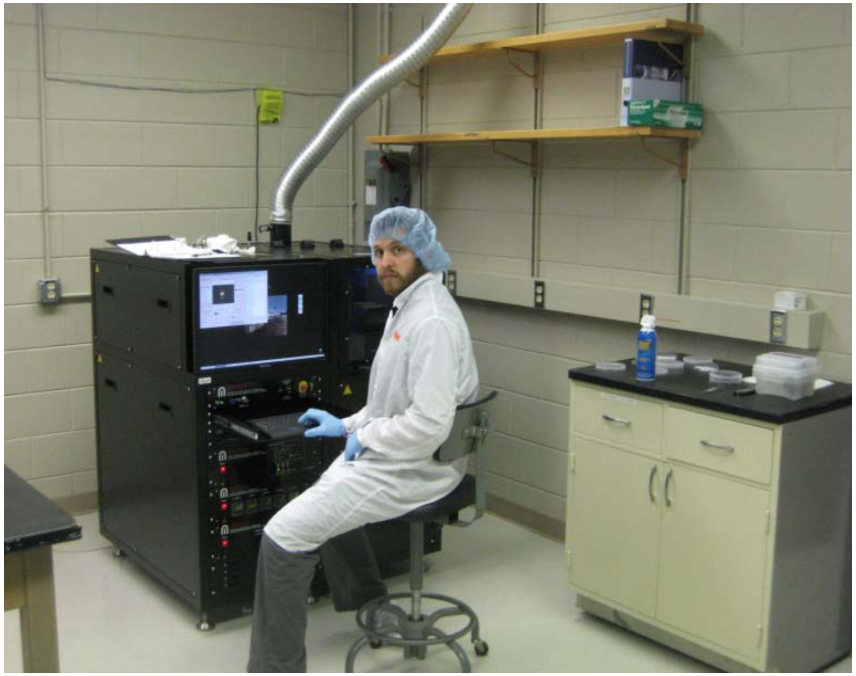
Personal Motivation & Tactics:

- Generate “new” science
- Transition into “real” products or applications
- Use combination of disciplines
  - electrical engineering + materials science
- Use combination of tools
  - Top-down + bottom up manufacturing methods

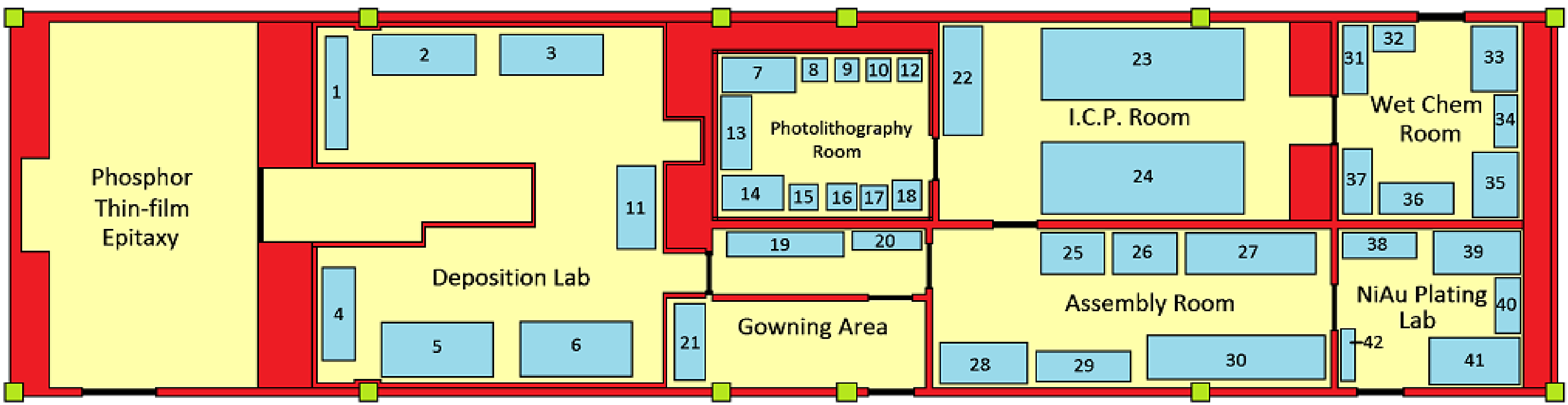


- CNTs have been produced in-house via Chemical Vapor Deposition (CVD) since 2003.
  - Catalyzed pyrolytic decomposition of hydro-carbon gasses
    - Ethylene (C_2H_4)
    - Methane (CH_4)
    - Acetylene (C_2H_2)

- But even better for making CNTs is the "Black Magic"
  - via DURIP funding from ONR in 2010
  - PECVD + TECVD



3,000 sq.ft. Class 100/10 Cleanroom

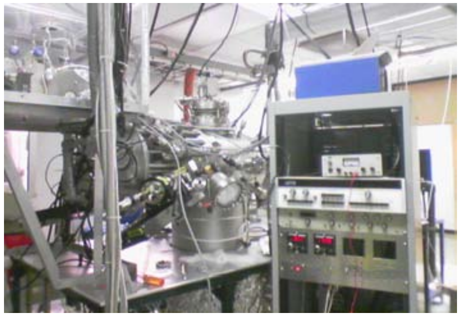


1 - Laminar Flow Hood
2 - Veeco E-Beam Evaporator
3 - Dual Chamber Evaporator
4 - Tube Furnace
5 - DC Sputter System (Sputter System 2)
6 - RF Sputter System (Sputter System 1)
7 - Wet Chem Area/ Laminar Flow Hood
8 - Oven
9 - Mask Aligner (Suss MJB4)
10 - Microscope (Olympus Vanox-T)
11 - Computer
12 - Computer
13 - Sample Storage
14 - Spincoater (P6000)
15 - Plasma Etcher (PDE/PDS 301)
16 - Spincoater (P6700)
17 - Profilometer (Alpha-Step)
18 - Mask Aligner (Suss MJB3)
19 - Sample Storage
20 - Supplies Storage
21 - Gown Storage
22 - Air Filtration
23 - Pegasus Etching System
24 - ICP Etching System
25 - Dicing Saw (MA1006)
26 - Die Attach
27 - Gas Storage
28 - Solder Reflow Station (SST 1200)
29 - Wire Bonder (West Bond)
30 - Work Area
31 - Glassware Storage
32 - Acid Storage
33 - Laminar Flow Hood
34 - Ultrapure Water Filtration
35 - Fume Hood
36 - Electrical Analysis Station
37 - Probe Station
38 - Work Area
39 - Electroplating Tanks/Fume Hood
40 - Ovens
41 - Fume Hood
42 - Chemical Storage

Pegasus DRIE
(Bosch Process for Si)

EvoVac
2 e-beams ea. w. 4 pockets
+ DC sputterer
+ RF sputterer
+ 4 Thermal Evaps

Ion Beam Assisted Deposition

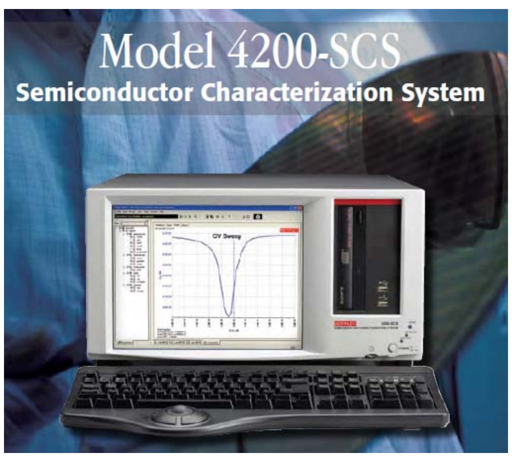


Molecular Beam Epitaxy

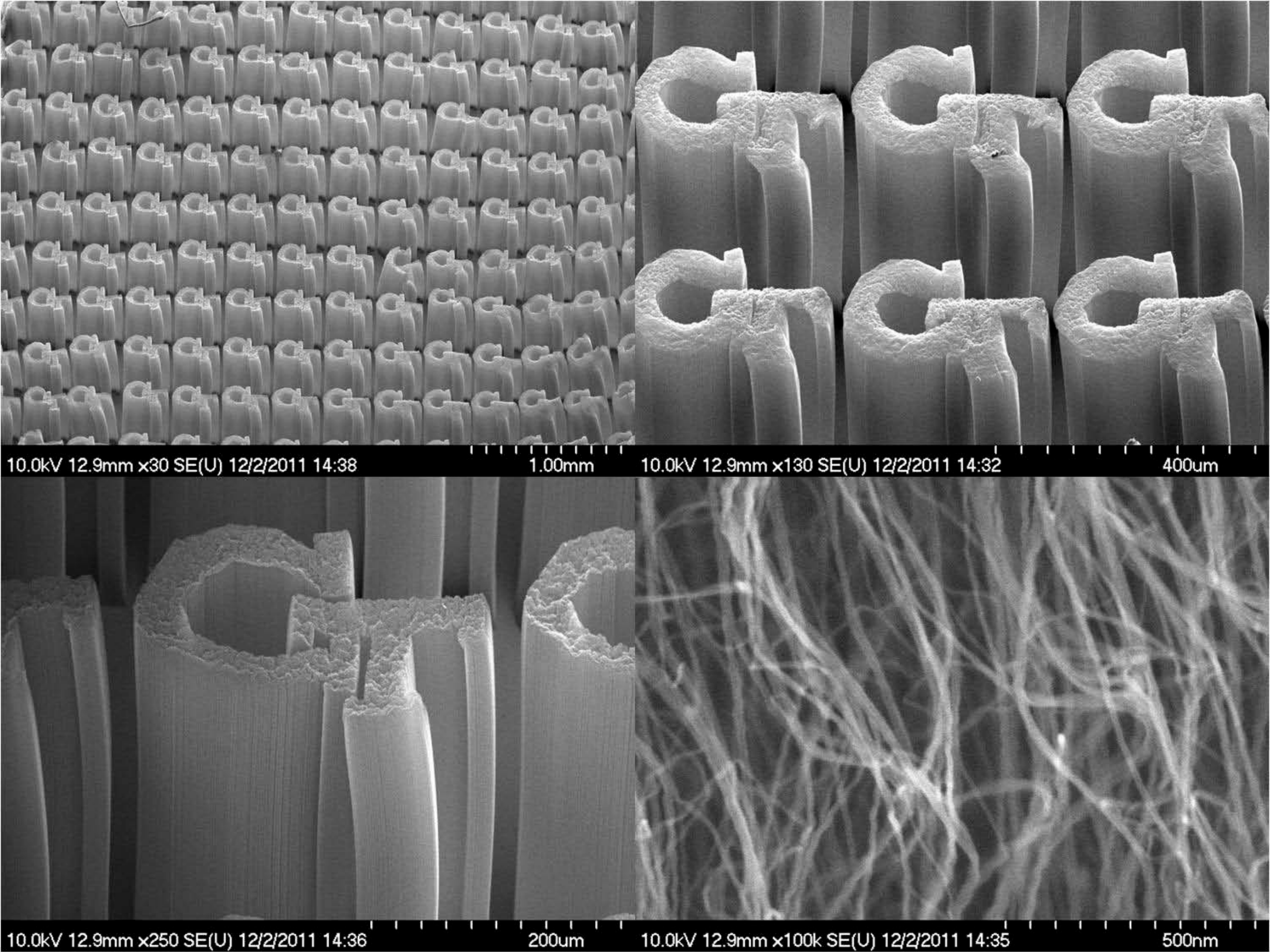
SUSS MJB4

STS ICP III-V

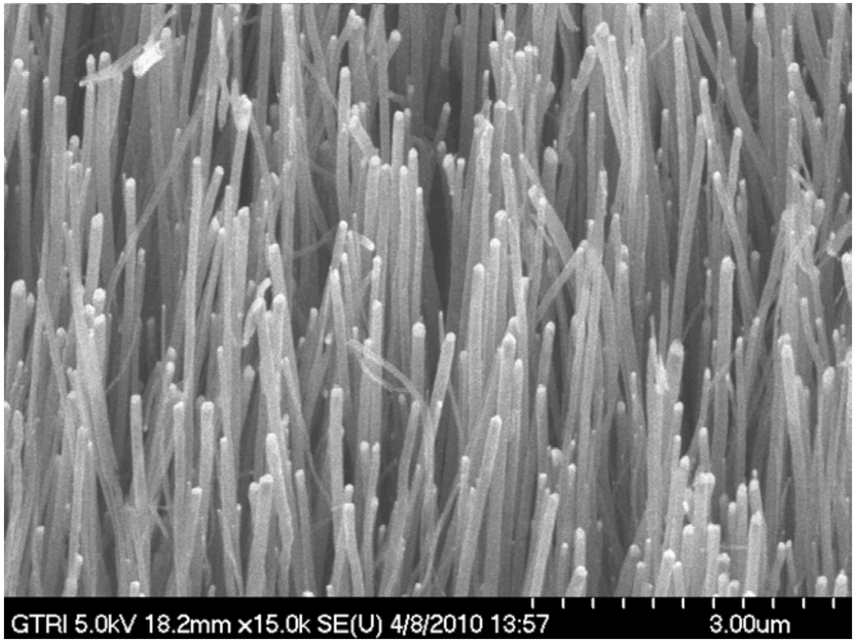
Hitachi S-4700

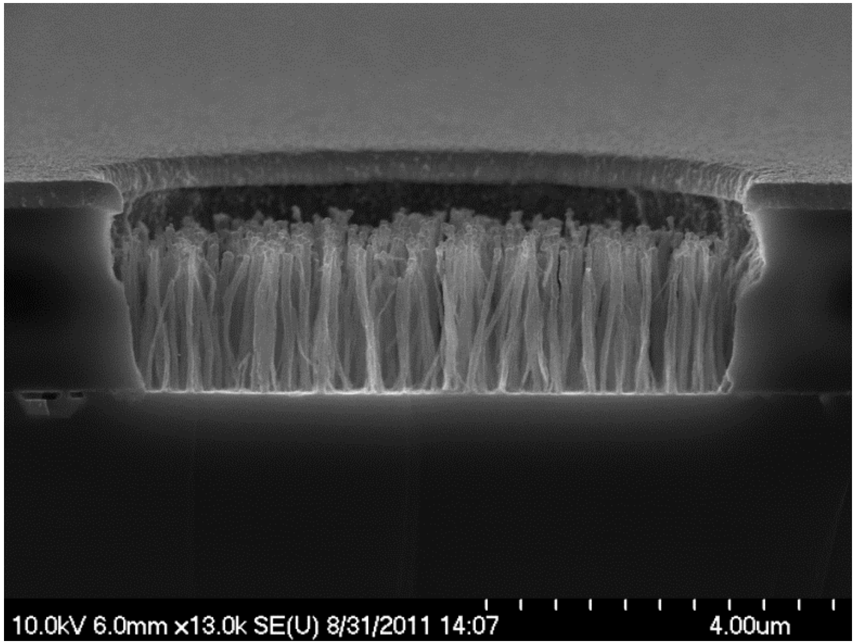


Solartron Impedance Spectroscopy

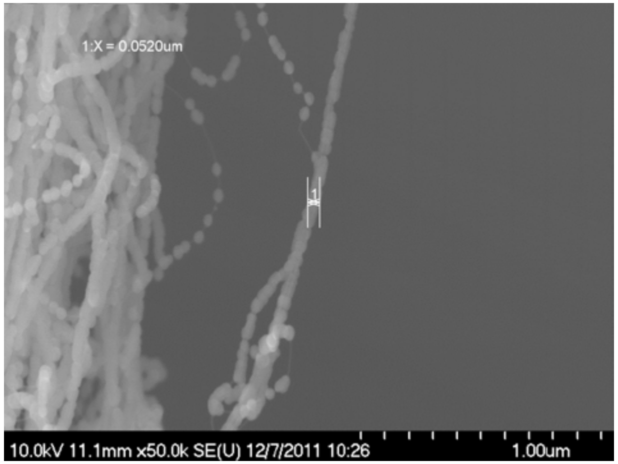

10.0kV 12.9mm x30 SE(U) 12/2/2011 14:38
1.00mm
10.0kV 12.9mm x130 SE(U) 12/2/2011 14:32
400um
10.0kV 12.9mm x250 SE(U) 12/2/2011 14:36
200um
10.0kV 12.9mm x100k SE(U) 12/2/2011 14:35
500nm

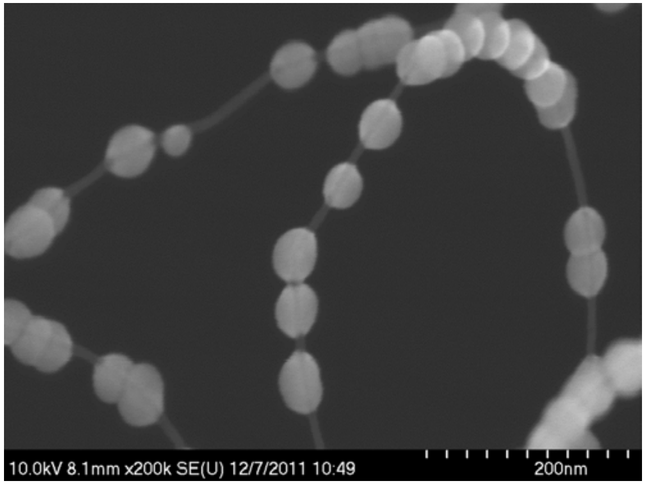
PECVD CNTs from Ni Catalyst

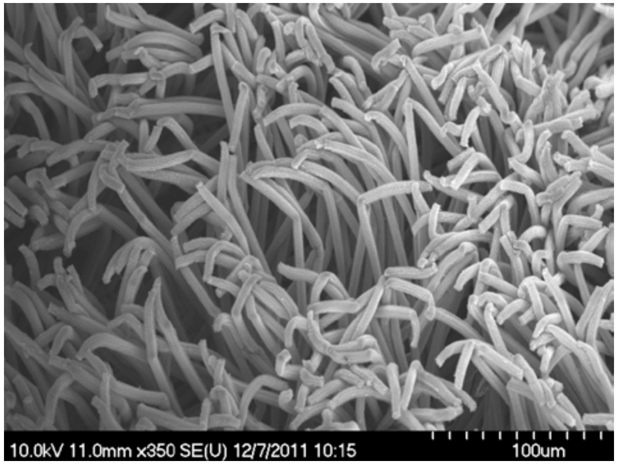


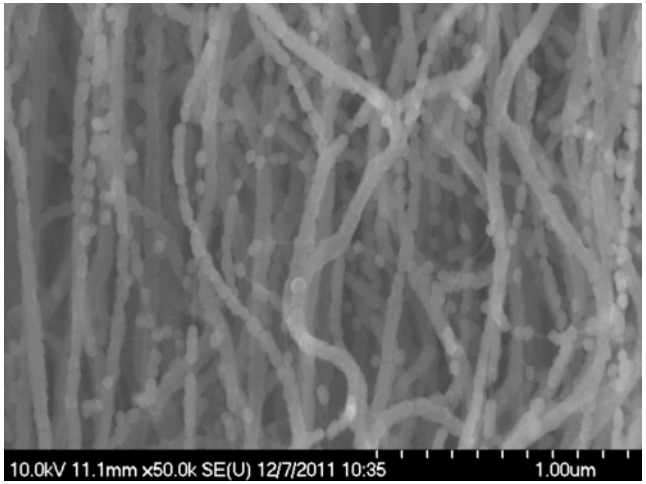


CNT Arrays with Al2O3

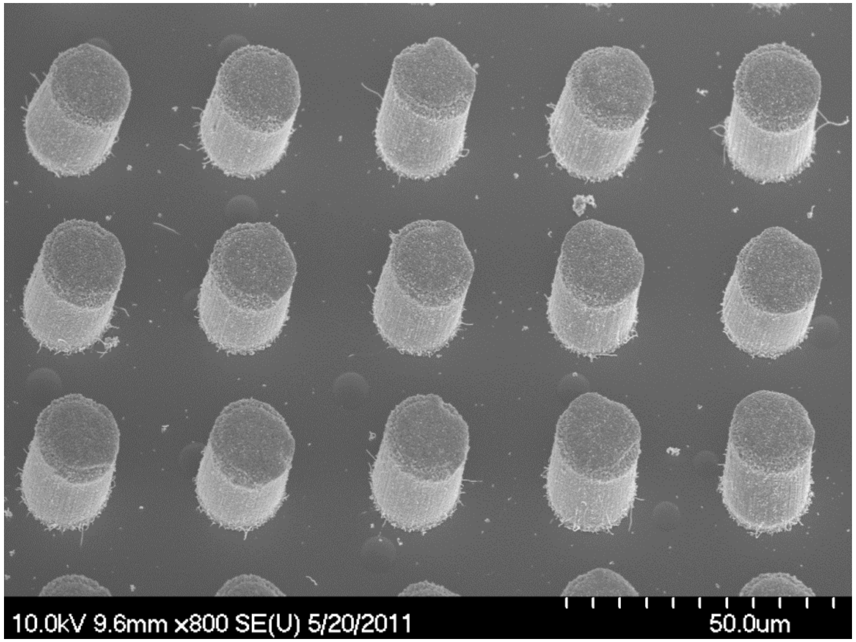


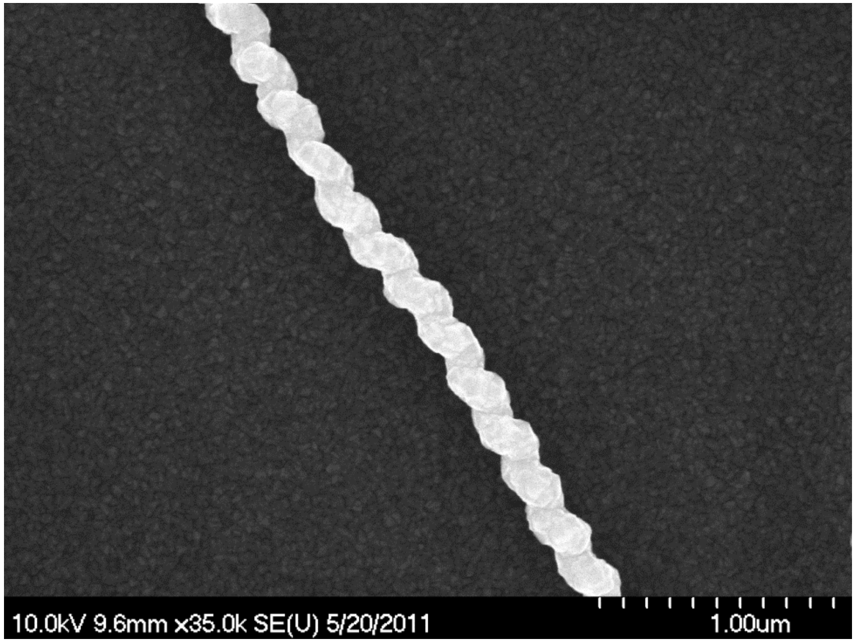






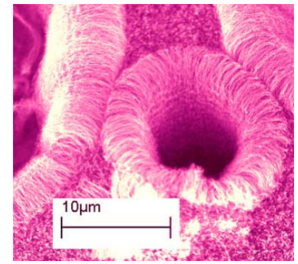
CNTs with ZnO ALD coating

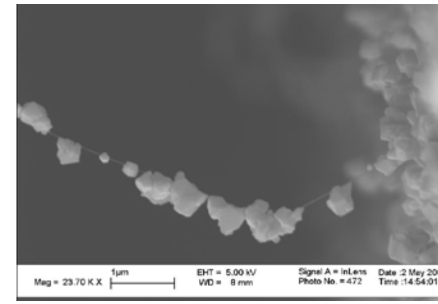


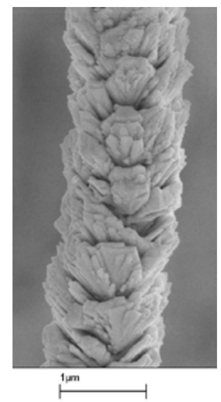


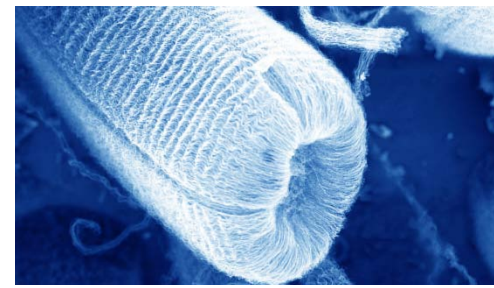
Overview of Programs

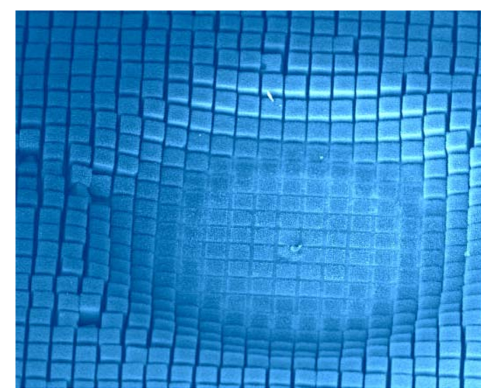
1. PV
2. Field Emission
3. Supercapacitors
4. Piezo
5. Li-ion Anodes
6. Drug Eluting Nanoelectrode arrays
7. Through Silicon Vias
8. Terascale Interconnects
9. Functionalized Fabrics
10. B_4C
11. Reliability
12. Antenna
13. Reactive Nano-Particles / Anti-Fouling
14. Direct-to-Discovery
15. Aligned Growth on Foils







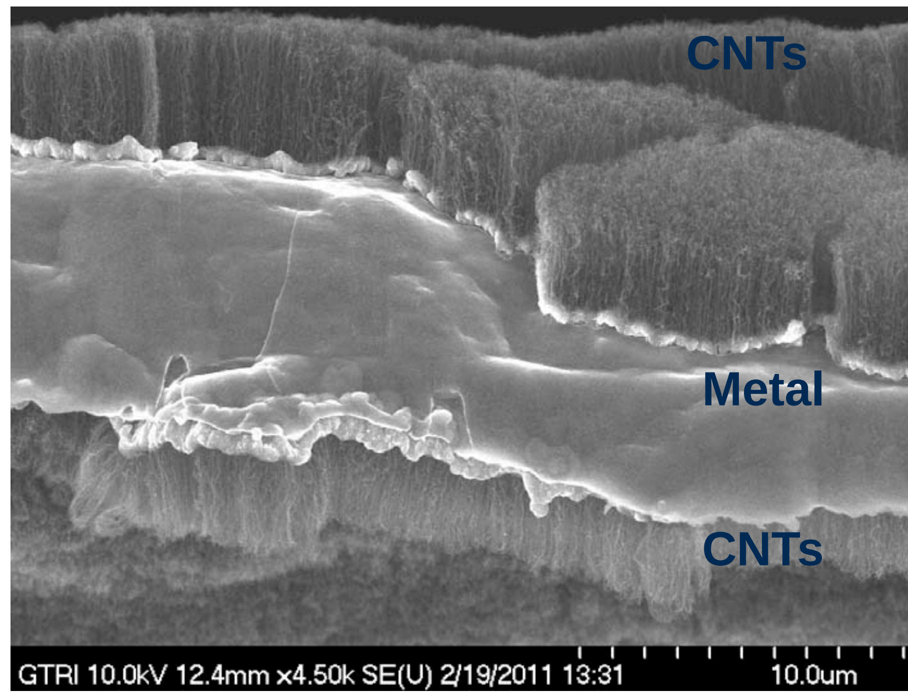


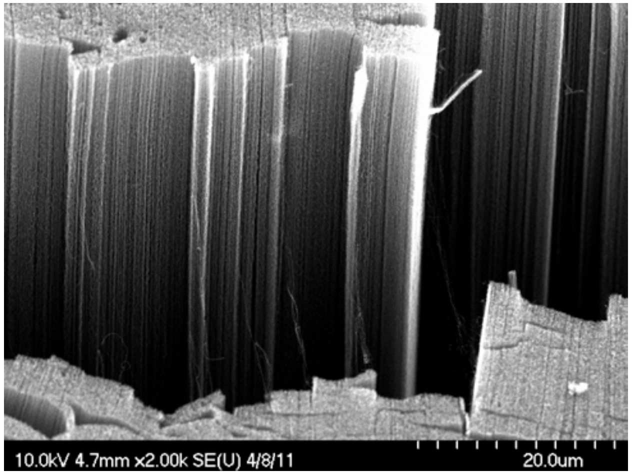


VACNT Growth on Metallic Substrates

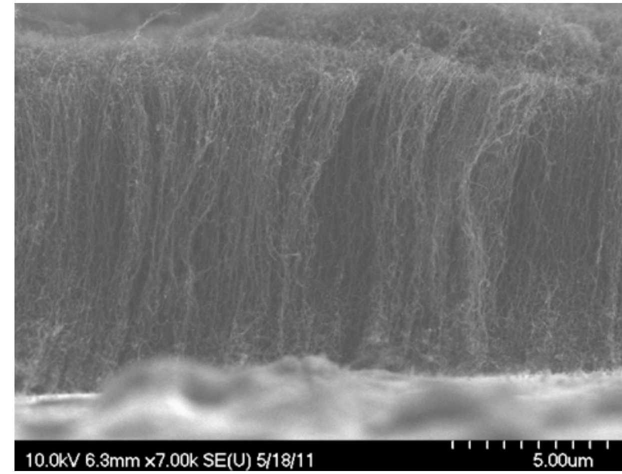
Joint work with Bara Cola (GT-ME)

- Conductive substrates needed to better utilize CNT properties and make efficient electrical and/or thermal contact
- Use only metallic support layers less than 100 nm in thickness
    - Also no support layers are possible for some metals
- VACNT heights can reach > 100 μm



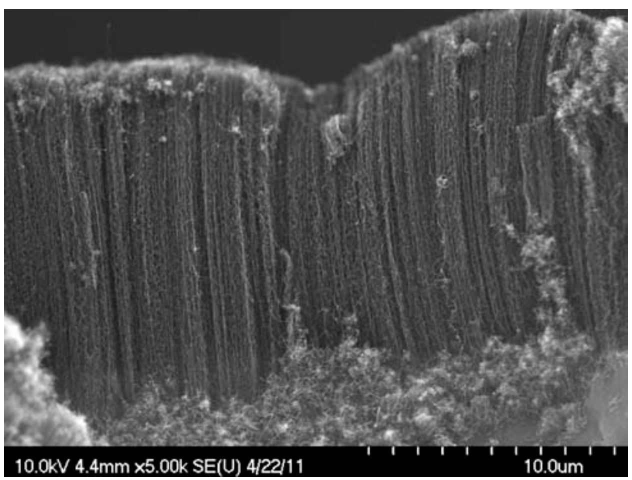


Cu

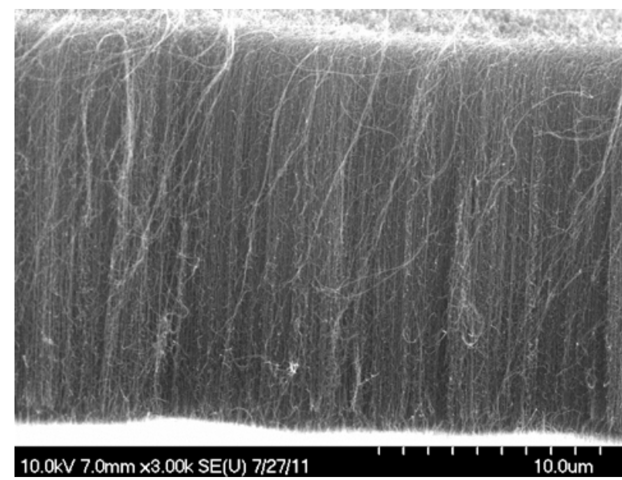


Stainless Steel

CNT Growth: Thermal Chemical Vapor Deposition (TCVD) >700 °C



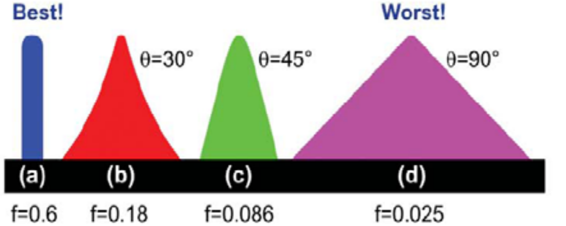
Al



Inconel

Field Emission from CNTs

- Low Work Function (5eV)
- Low "Turn-on" voltage
- High Aspect Ratio
- Non-blunting
- Field Screening

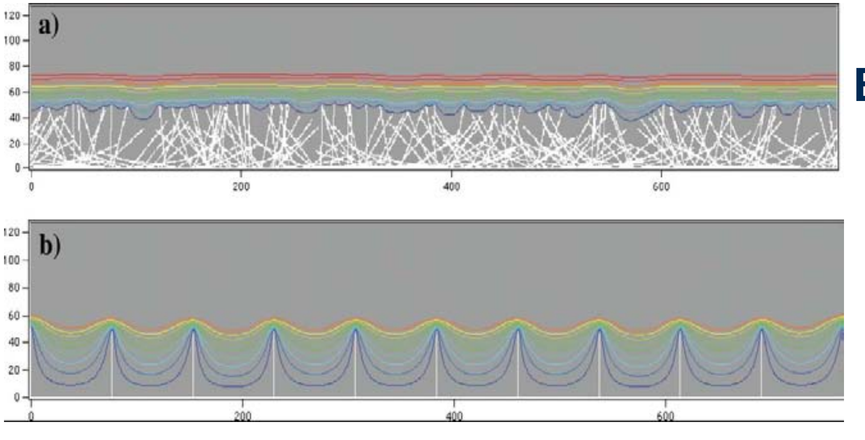


•T. Utsumi, *IEEE Trans. Electron Dev.*, 1991, 38, 2276.

$$E = \beta V$$

$$\frac{I}{V^2} = \frac{\alpha\, a\, \beta^2}{\phi} \exp\left(\frac{-b\,\phi^{3/2}}{\beta V}\right)$$

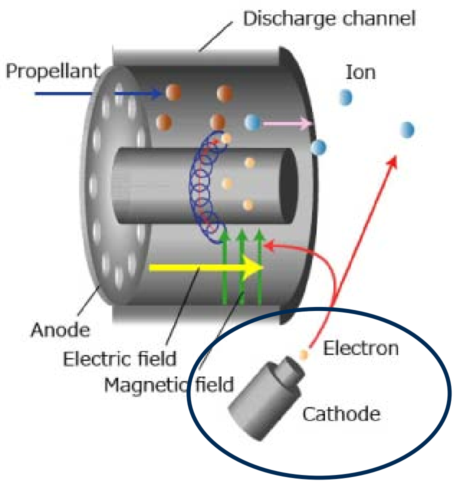
ϕ = work function
β = enhancement factor
a = emission area
E = electric field strength
V = gate voltage
I = emission current
α, b = constants



•K.B.K. Teo, et al. Nature, Vol. 437, 2005, pp. 968.

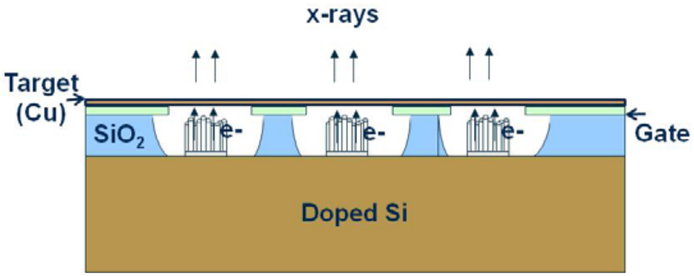
Field Emission

Cold Cathode for Hall Effect Thruster

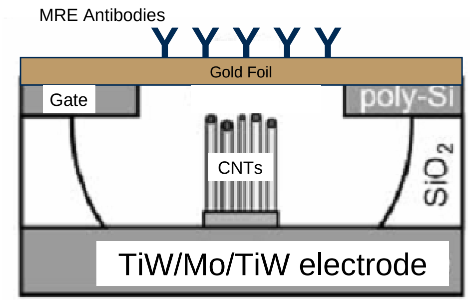


http://www.al.t.u-tokyo.ac.jp/hall/en/projects.html

X-ray Source (Portable)



Electron-induced Surface Plasmon Resonance (Chem-Bio Sensor)



Doped Si

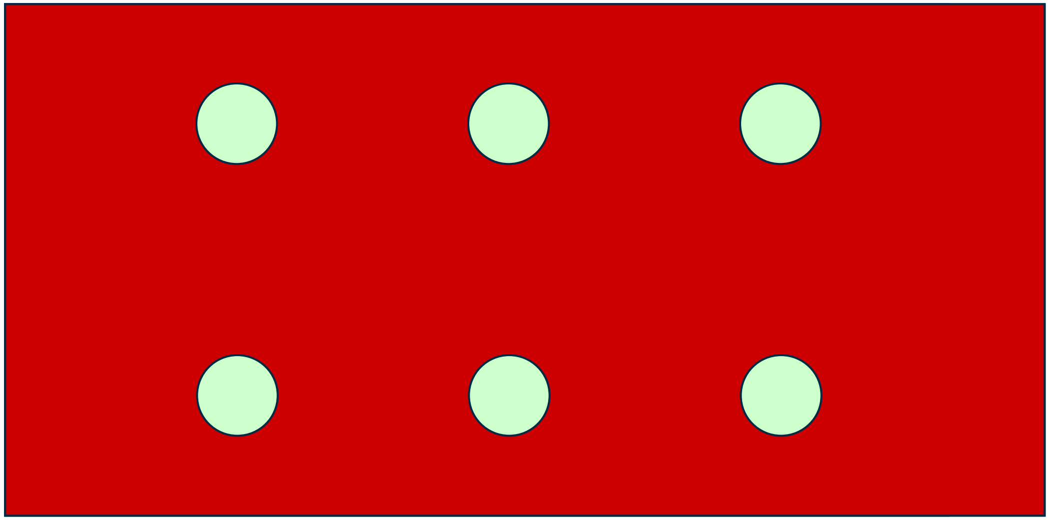
- Deposit SiO2 (~10μm)
- Variable for Height

- Deposit gate
- (poly Si or Cr, ~200nm)

plan view

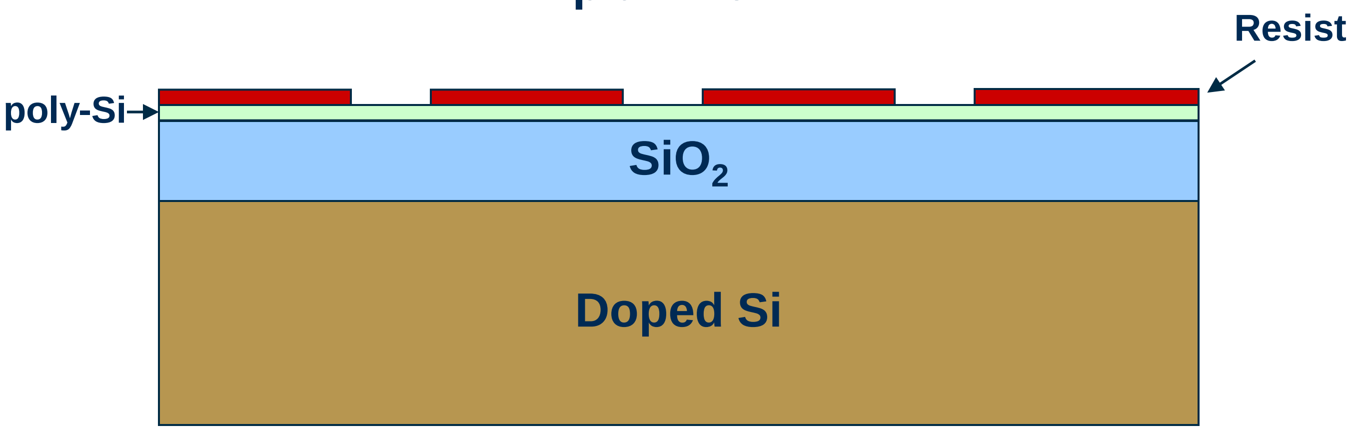
Spincoat Photoresist

elevation view

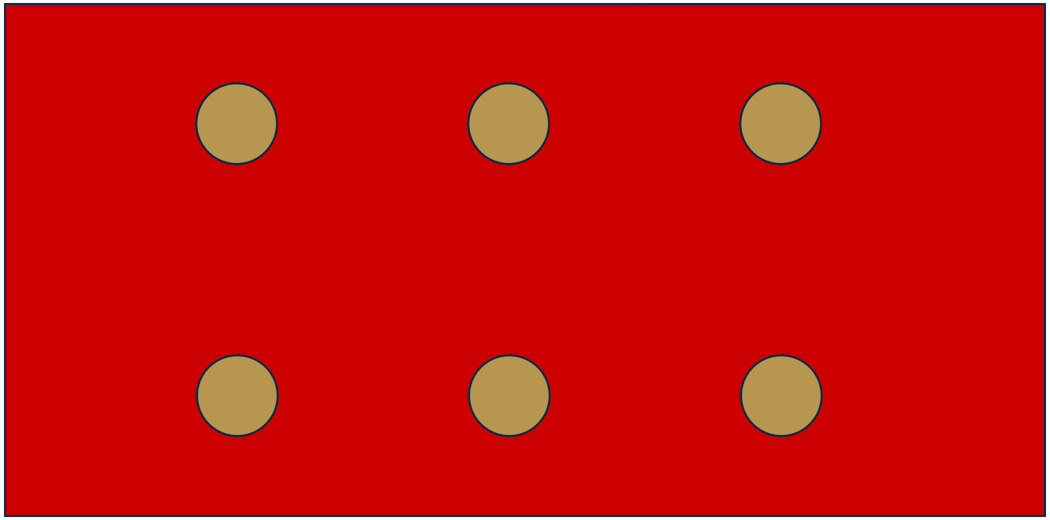


plan view

- Pattern
- Develop

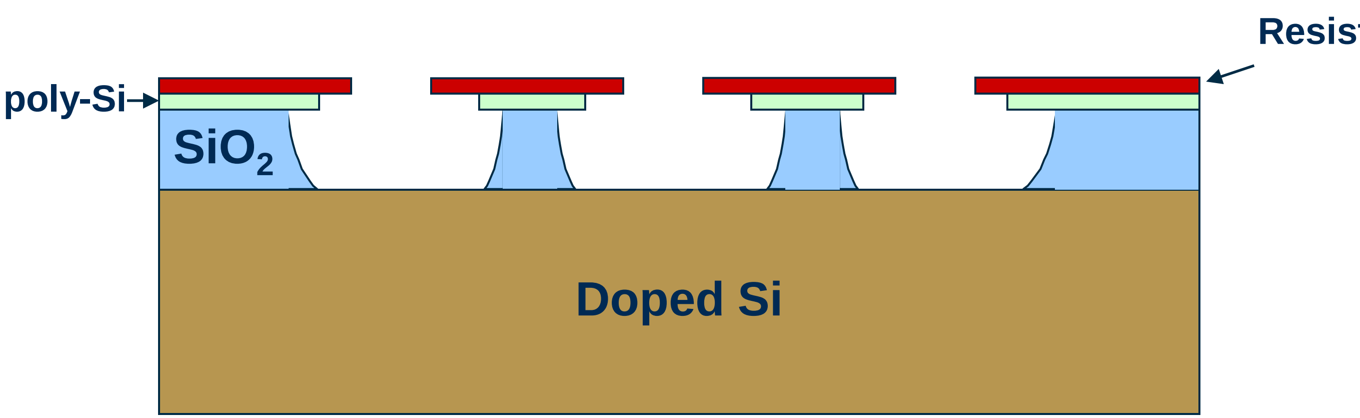


elevation view



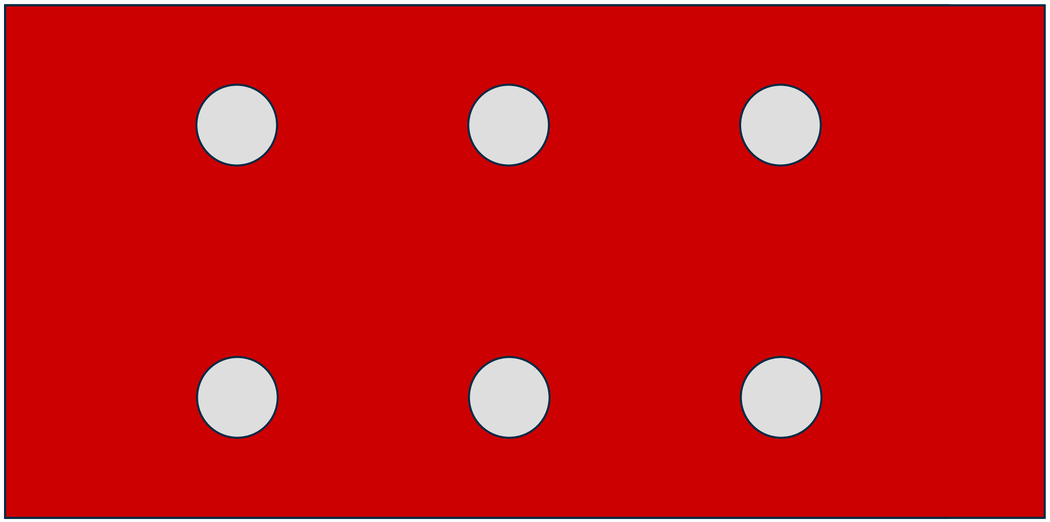
plan view

•Etch gate and insulator isotropically

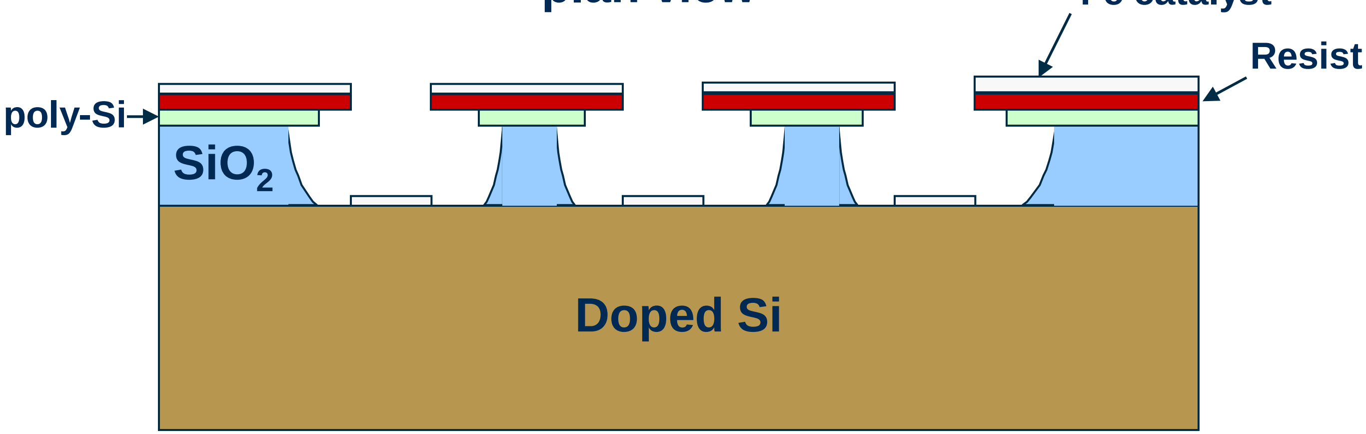


elevation view

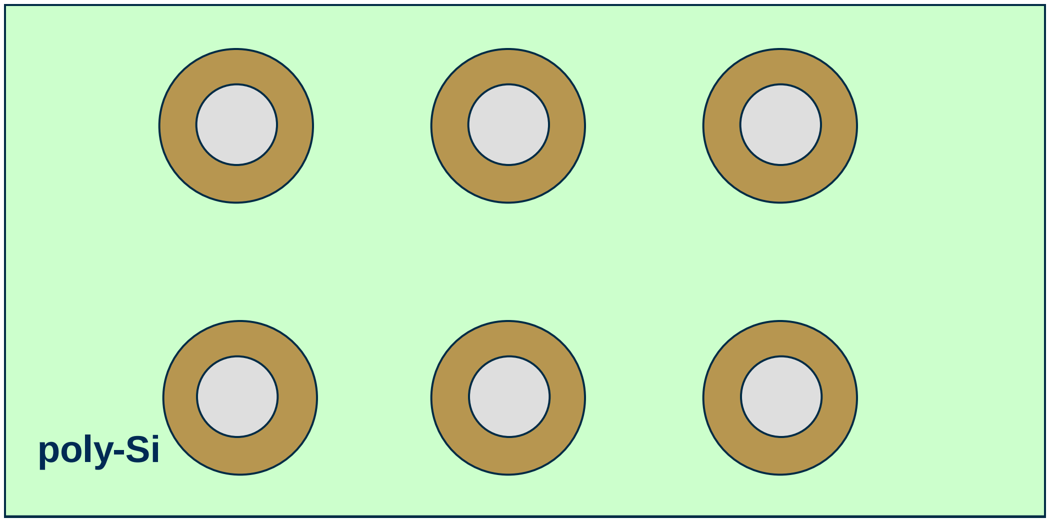
- Deposit catalyst metal
- Fe shown
- Ni possible with barrier layers



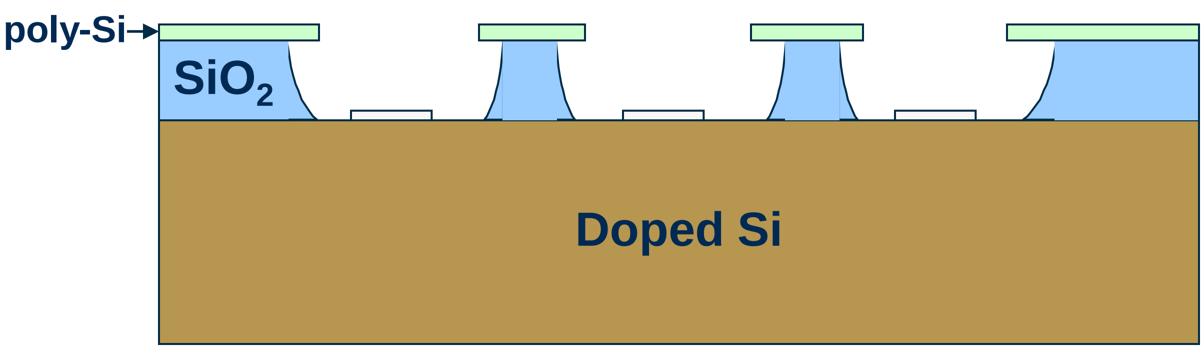
plan view



elevation view

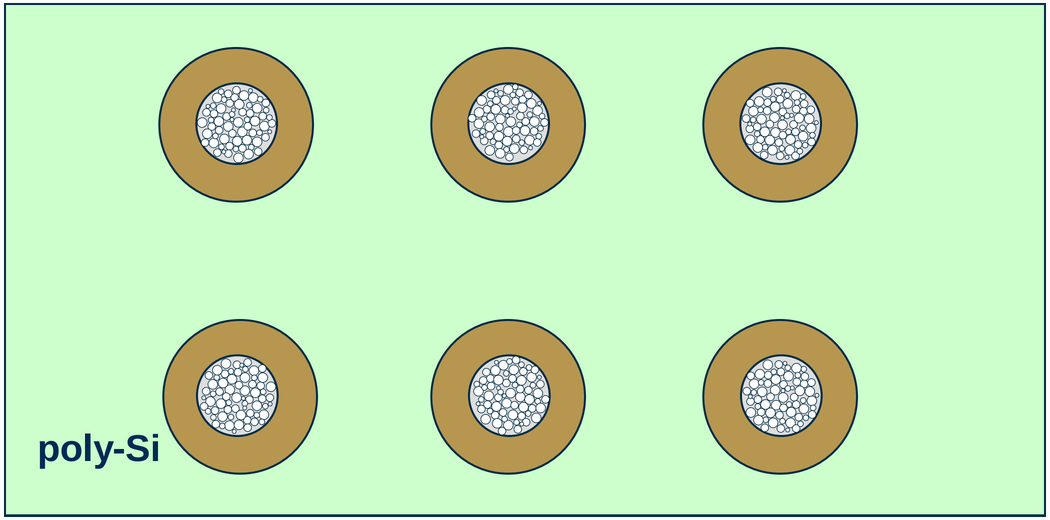


plan view

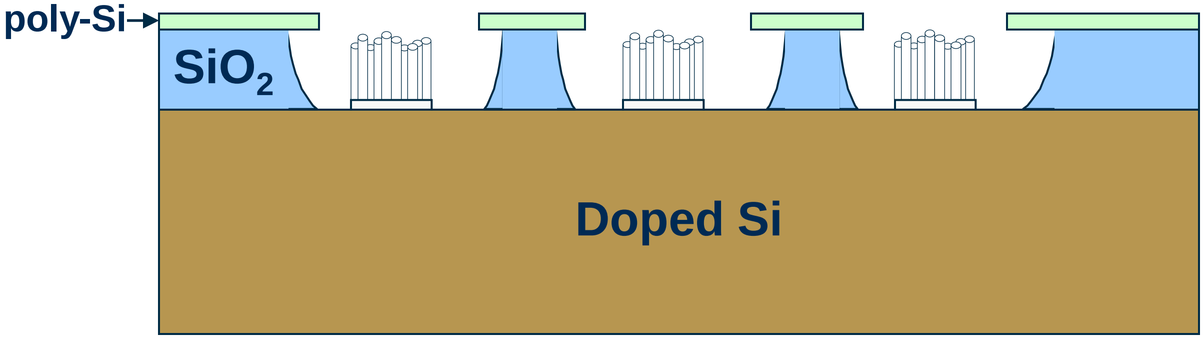


elevation view

Lift off & Dice



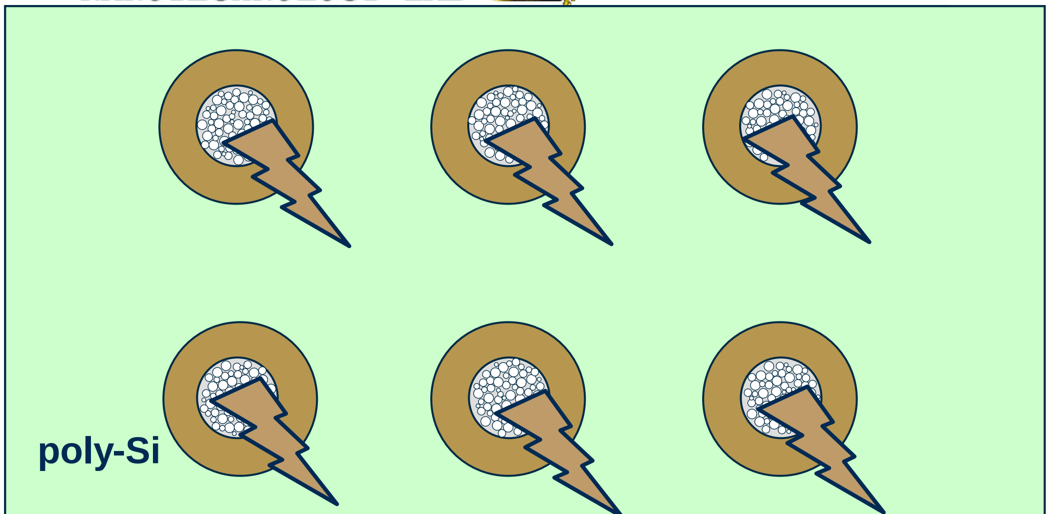
plan view



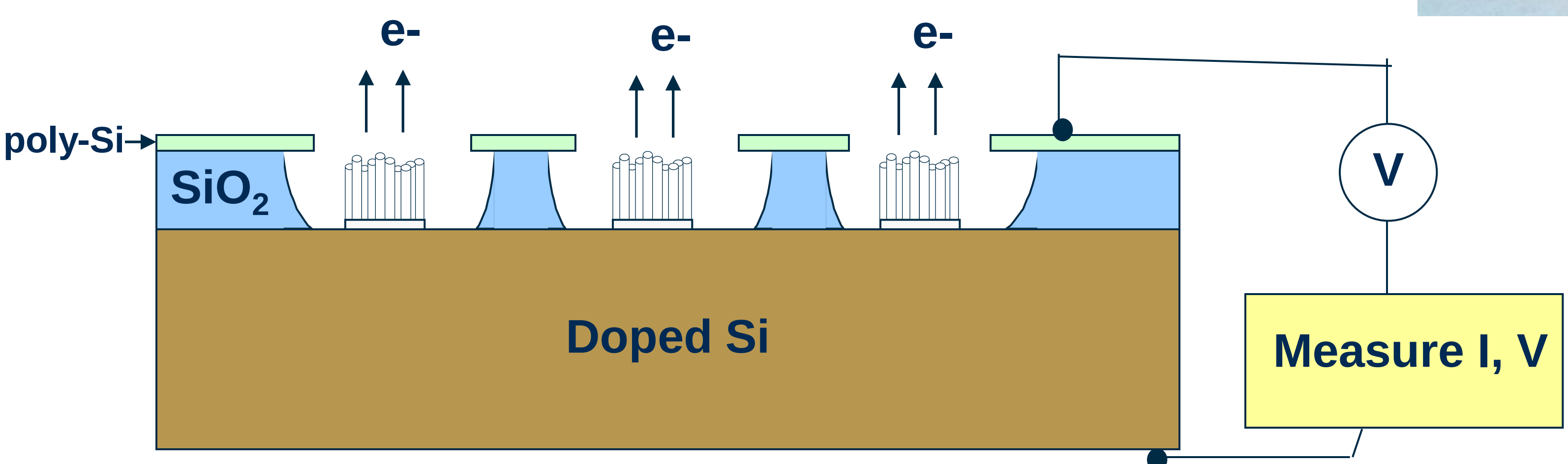
elevation view

- Grow CNTs

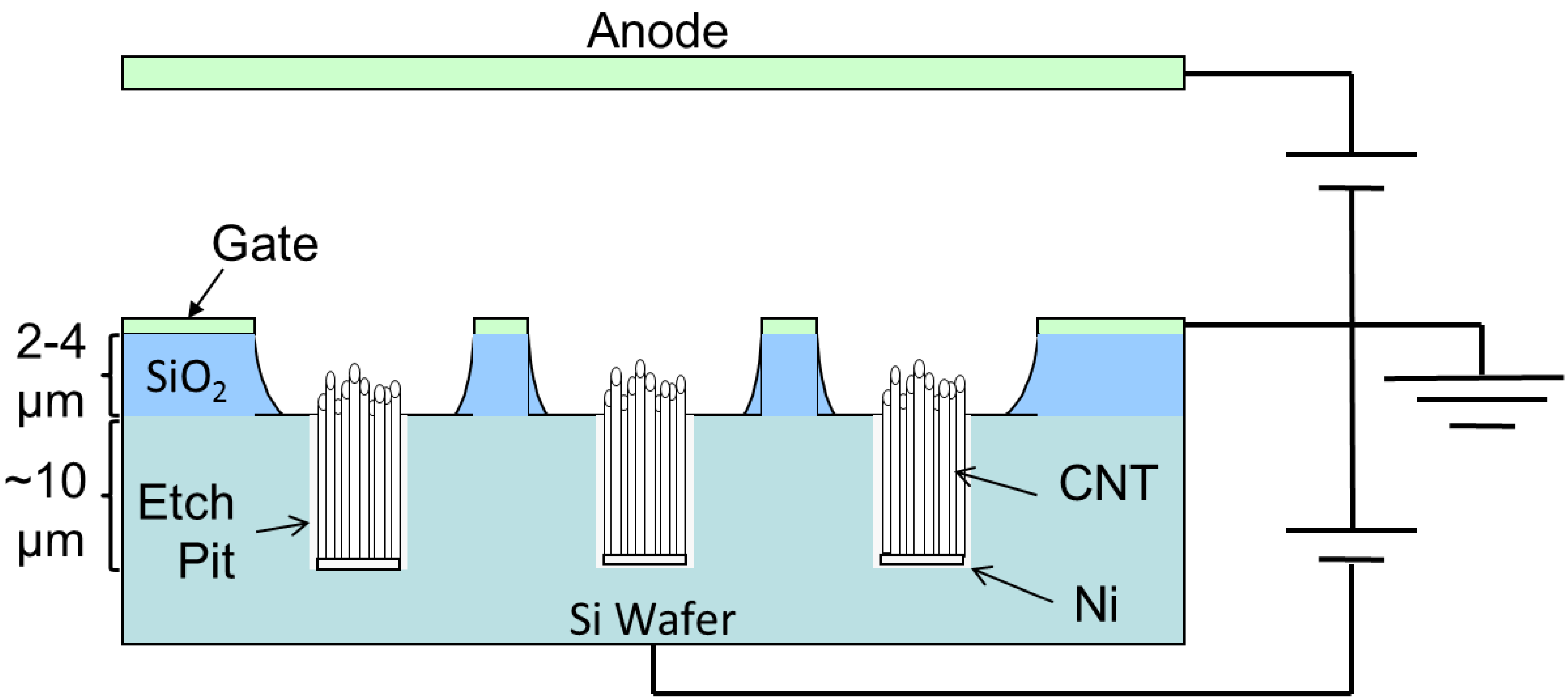
- Connect and test @ HPEPL
- Langmuir Probe

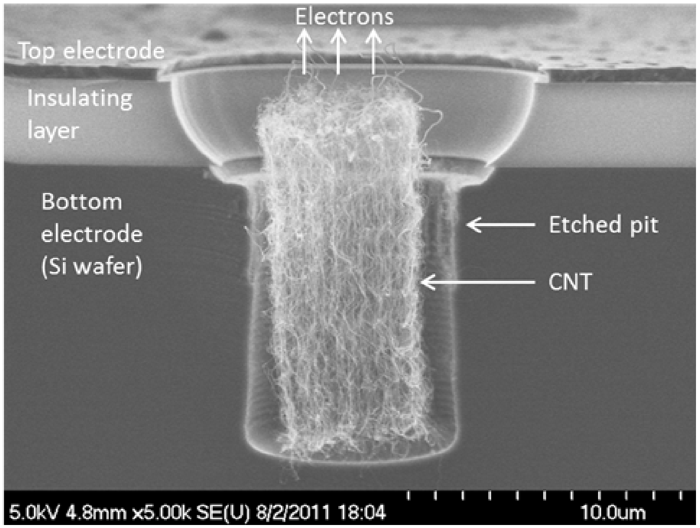


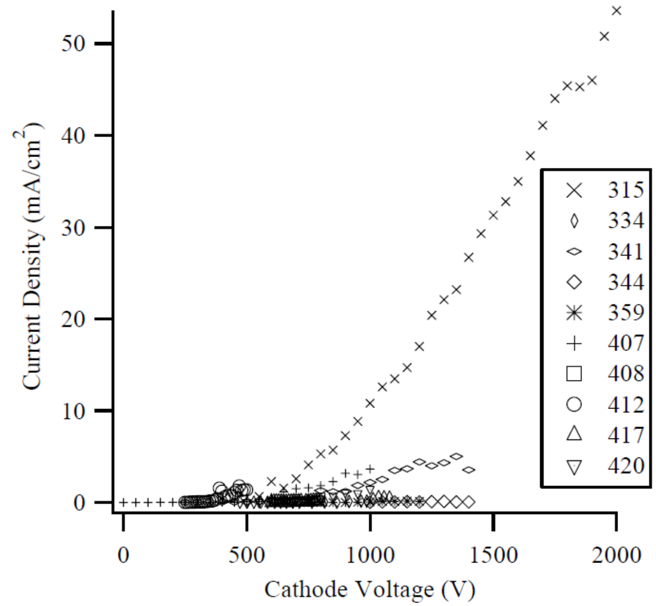
plan view

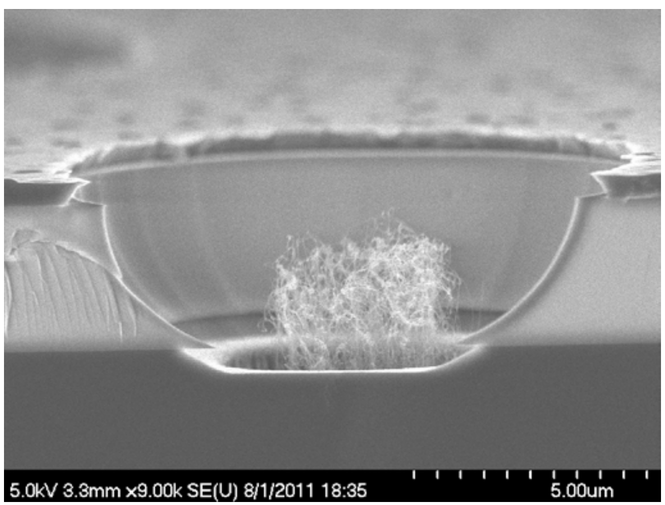


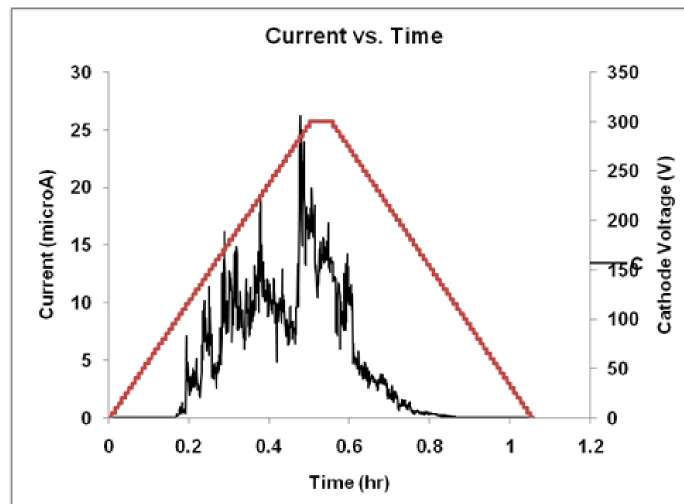
elevation view

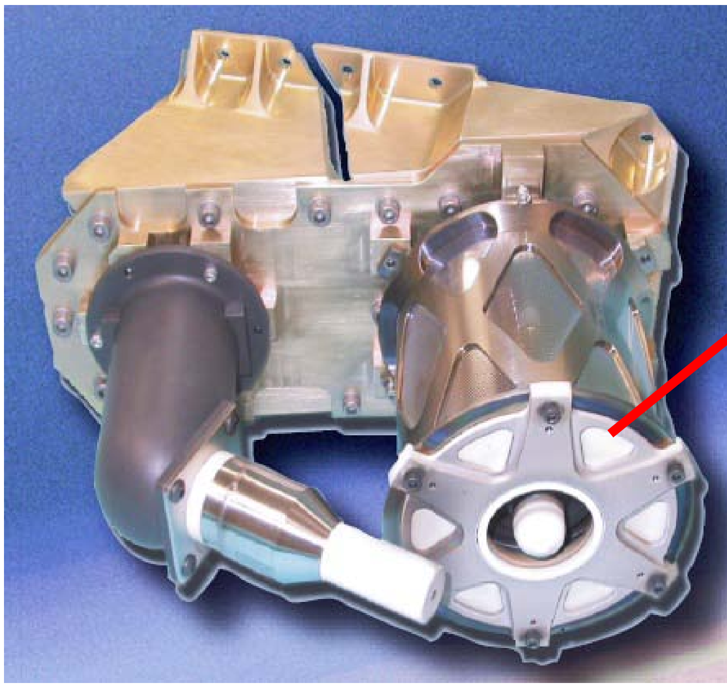

Anode
Gate
2-4 μm
SiO_2
~10 μm
Etch Pit
CNT
Ni
Si Wafer

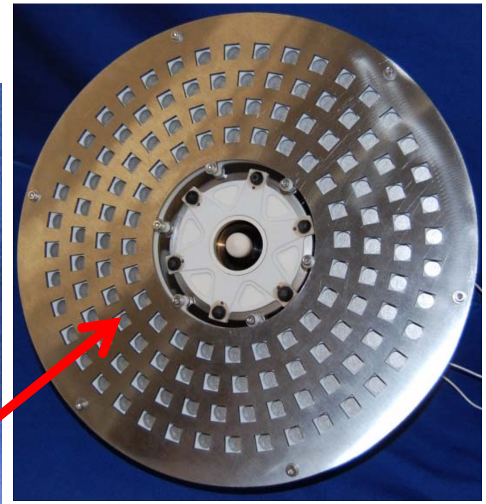

Electrons
Top electrode
Insulating layer
Bottom electrode (Si wafer)
Etched pit
CNT
5.0kV 4.8mm x5.00k SE(U) 8/2/2011 18:04
10.0um

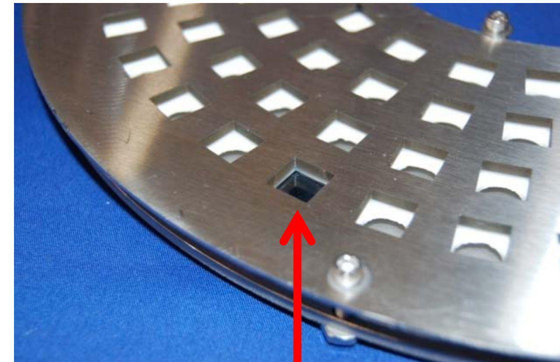

Current Density (mA/cm²)
Cathode Voltage (V)
315
334
341
344
359
407
408
412
417
420


5.0kV 3.3mm x9.00k SE(U) 8/1/2011 18:35
5.00um


Current vs. Time
Current (microA)
Cathode Voltage (V)
Time (hr)



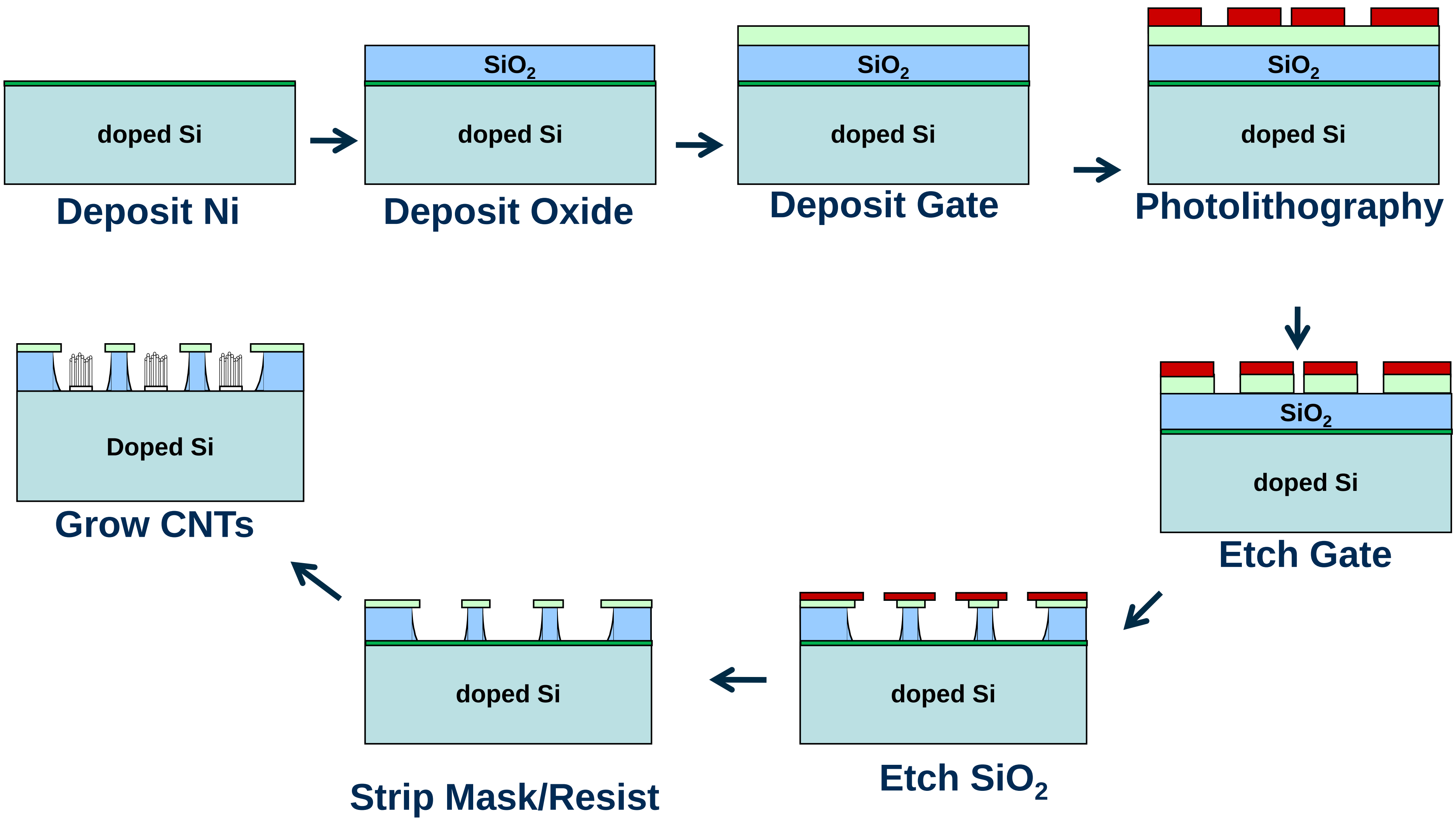




84 Emitter Capacity

2.1 A at 25 mA/cm2

Busek BHT-200 Modified for use with CNT Emitters


doped Si
Deposit Ni
SiO2
doped Si
Deposit Oxide
SiO2
doped Si
Deposit Gate
SiO2
doped Si
Photolithography
SiO2
doped Si
Etch Gate
doped Si
Etch SiO2
doped Si
Strip Mask/Resist
Doped Si
Grow CNTs

CNT growth parameter for CNTs ≤ 2µm

CVD growth:

•N_2 and NH_3 flowed at 100sccm and 160scmm

•Temperature ramp of 300°C/min until 650°C (top and bottom heat)

•Annealed at 650°C for 2min

•Plasma Ignited: 80W, 15kHz, 800V

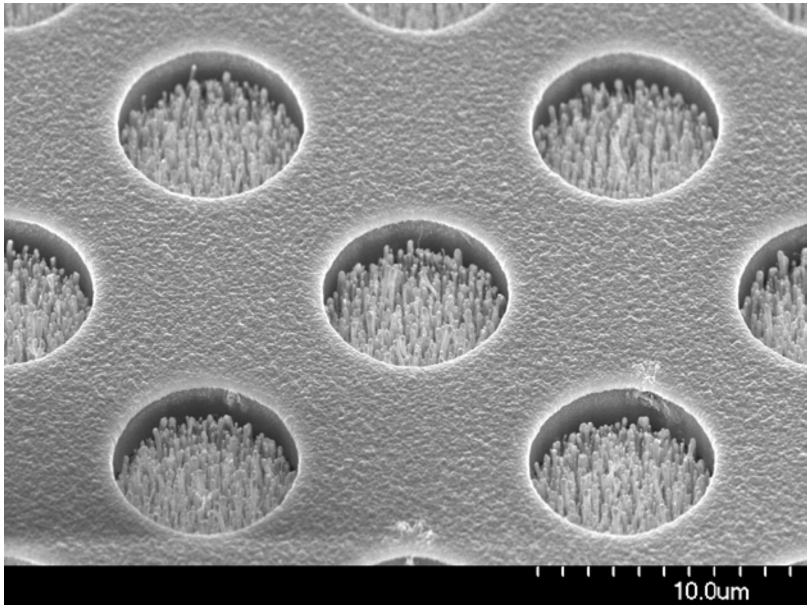
•Pressure controller activated: $P_{chamber}$ = 6mbar

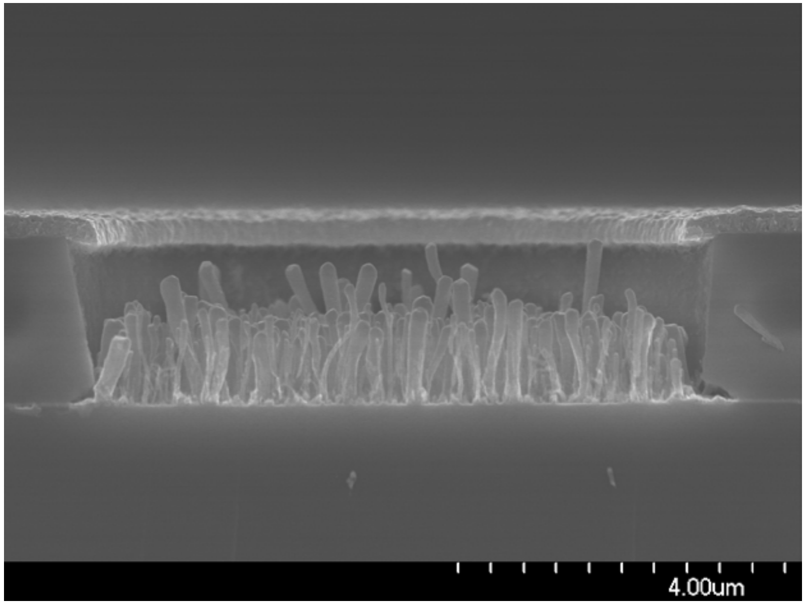
•Annealed under NH_3 plasma for 3 min while T raised to 750°C at rate of 200°C/min

•C2H2 (40sccm) introduced at end of plasma anneal

•Growth time = 6min

•Plasma extinguished, cooled under N_2 flow until T <400°C. Opened to atmosphere



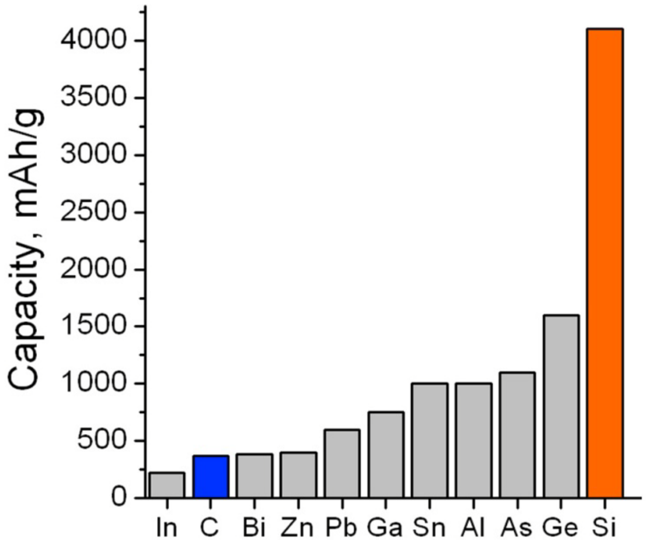


Future Research Directions

- Improved emission stability
- ‘Capping’ of Spindt pits

Si-coated Carbon Nanotubes for Li - ion battery anodes

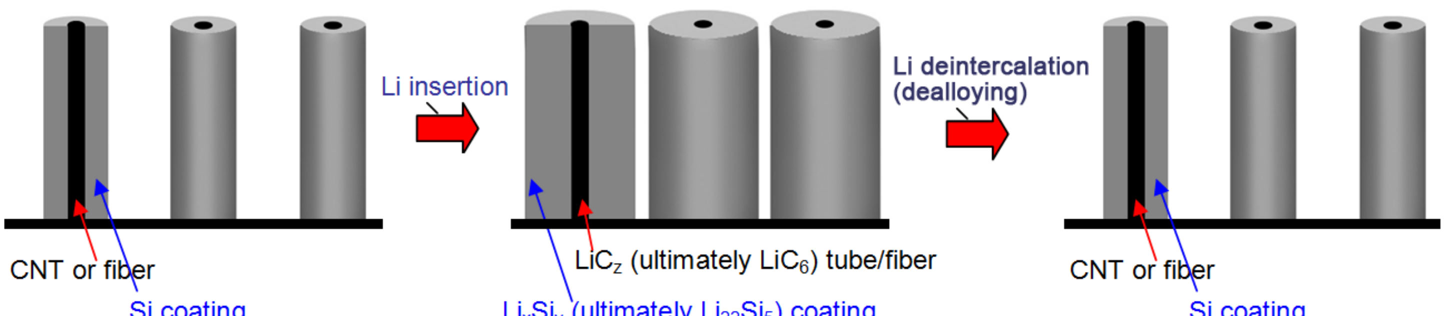
(with Yushin in MSE)

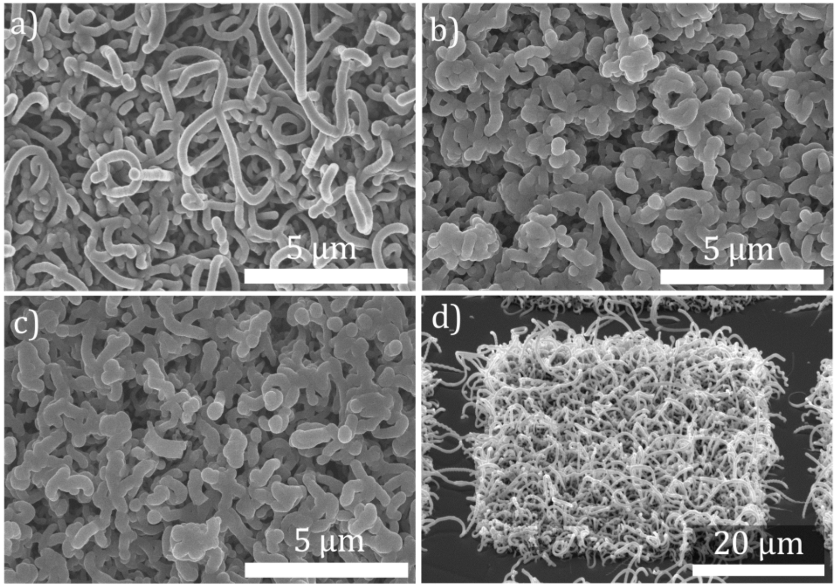


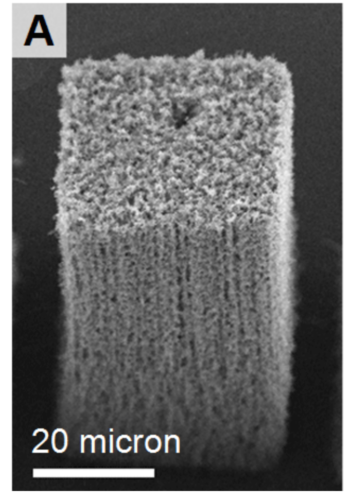
- **Silicon has an order of magnitude greater capacity compared to graphite anodes**
- **But Silicon has very poor cyclability (pulverizes with Lithium insertion)**
- **Solution = Reinforce Silicon (with Carbon Nanotubes)**

$$Li^{+} + e^{-} + \frac{1}{x}\times\frac{5}{22}Si \underset{k_a}{\overset{k_c}{\rightleftarrows}} \frac{1}{x}\times Li_xSi_{\frac{5}{22}}$$

Vertically aligned carbon nanotubes or fibers coated with Si

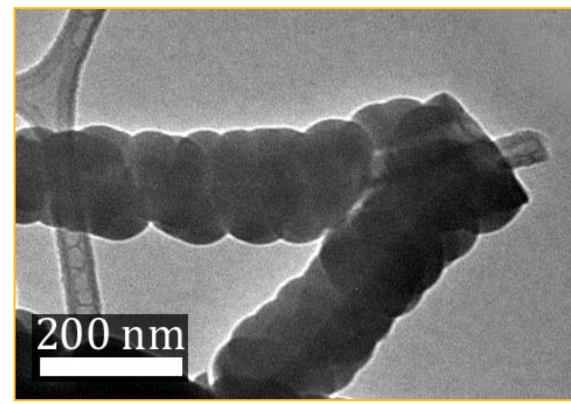




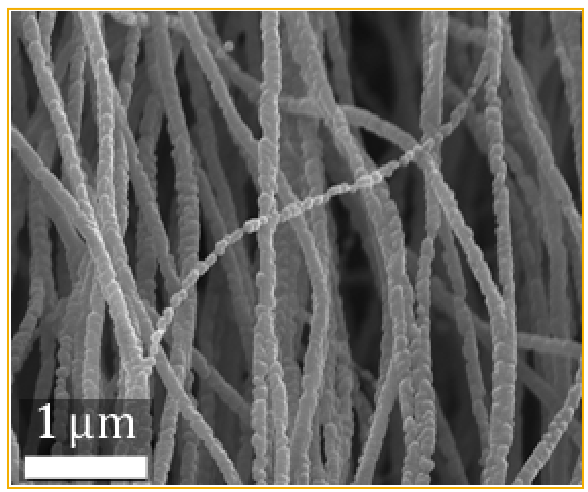


Vertically aligned carbon nanotubes

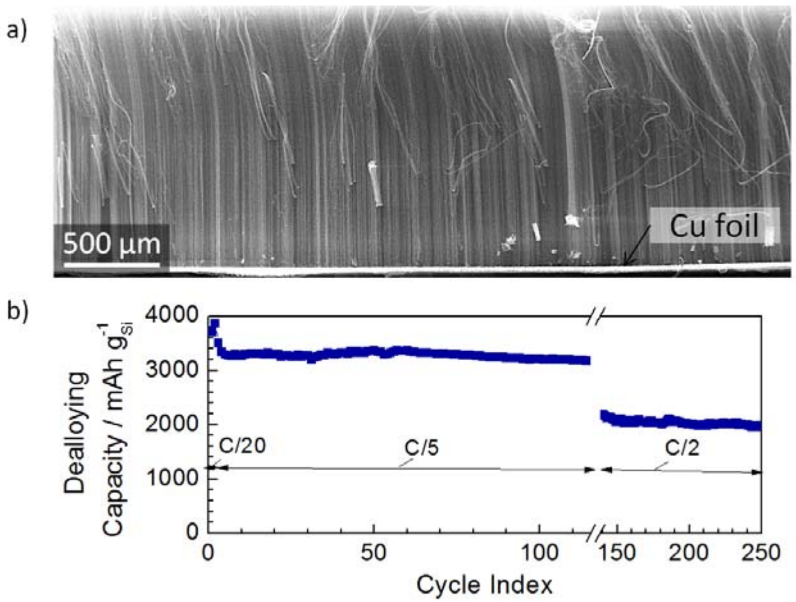
Act as "rebar" to strengthen internal structure of Si-battery

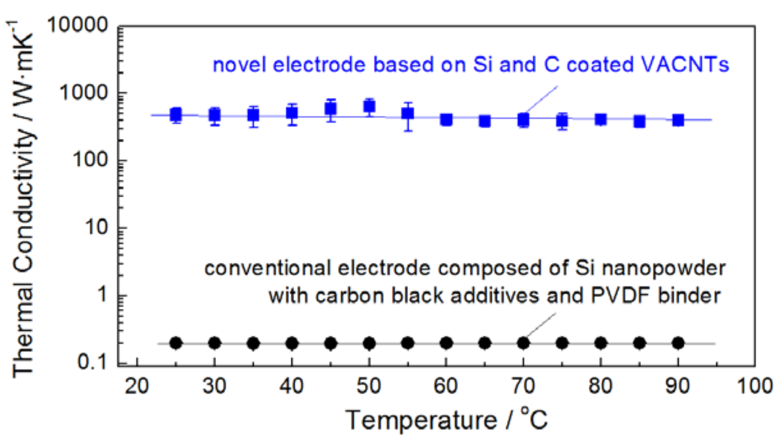


Pictures of Si-coated Carbon Nanotubes Demonstrates conformal coatings are possible



Charge/Discharge Results



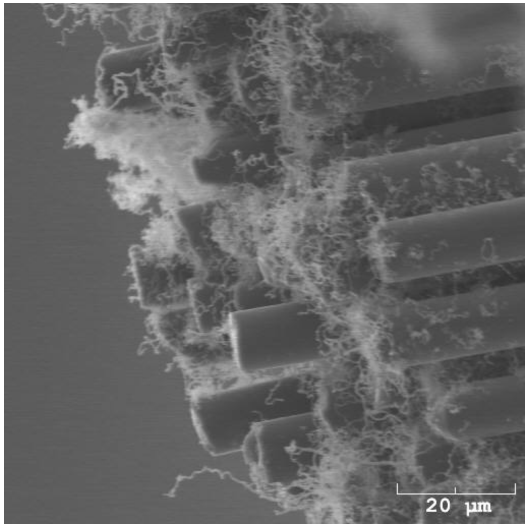


- **Generally stable performance and reversible dealloying capacity ~2000 mAh/g (over 5x more than graphite) has been demonstrated after 250 cycles.**
- **VACNTs provide structural support for Si as well as dramatically improved electrical and thermal conductivity therefore higher power Si-containing electrodes are possible.**

Joint Work with Gleb Yushin; GT-MSE

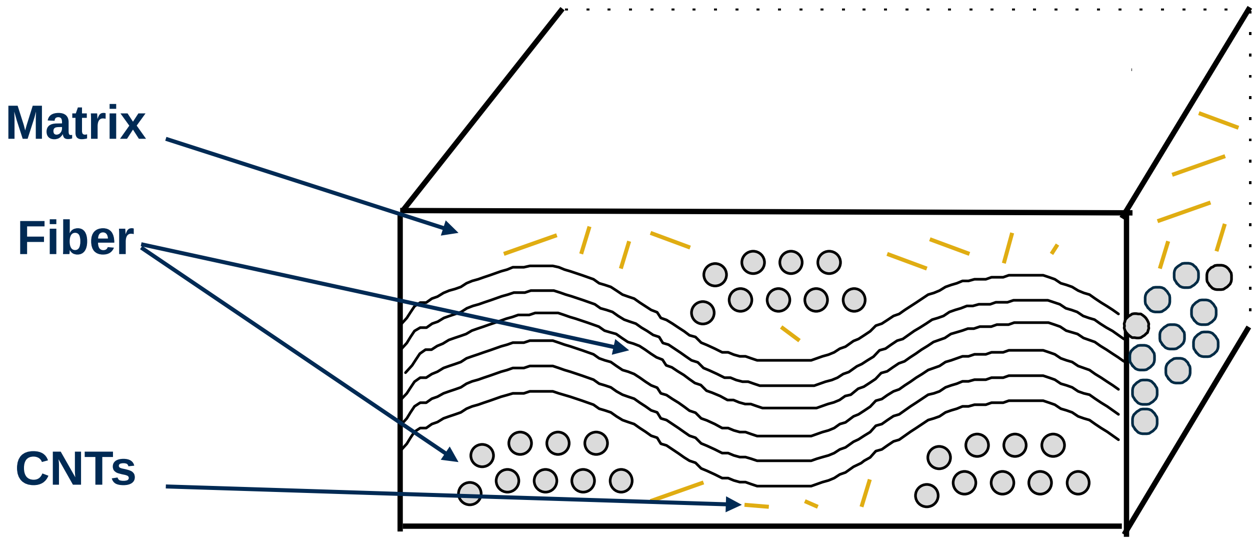
Future Research Directions

- **Understand the effect of electrolyte composition on stability of electrodes**
- **Examine effect of Si coating thickness on stability**
- **Utilize other Li-ion alloying materials (i.e., Ge)**

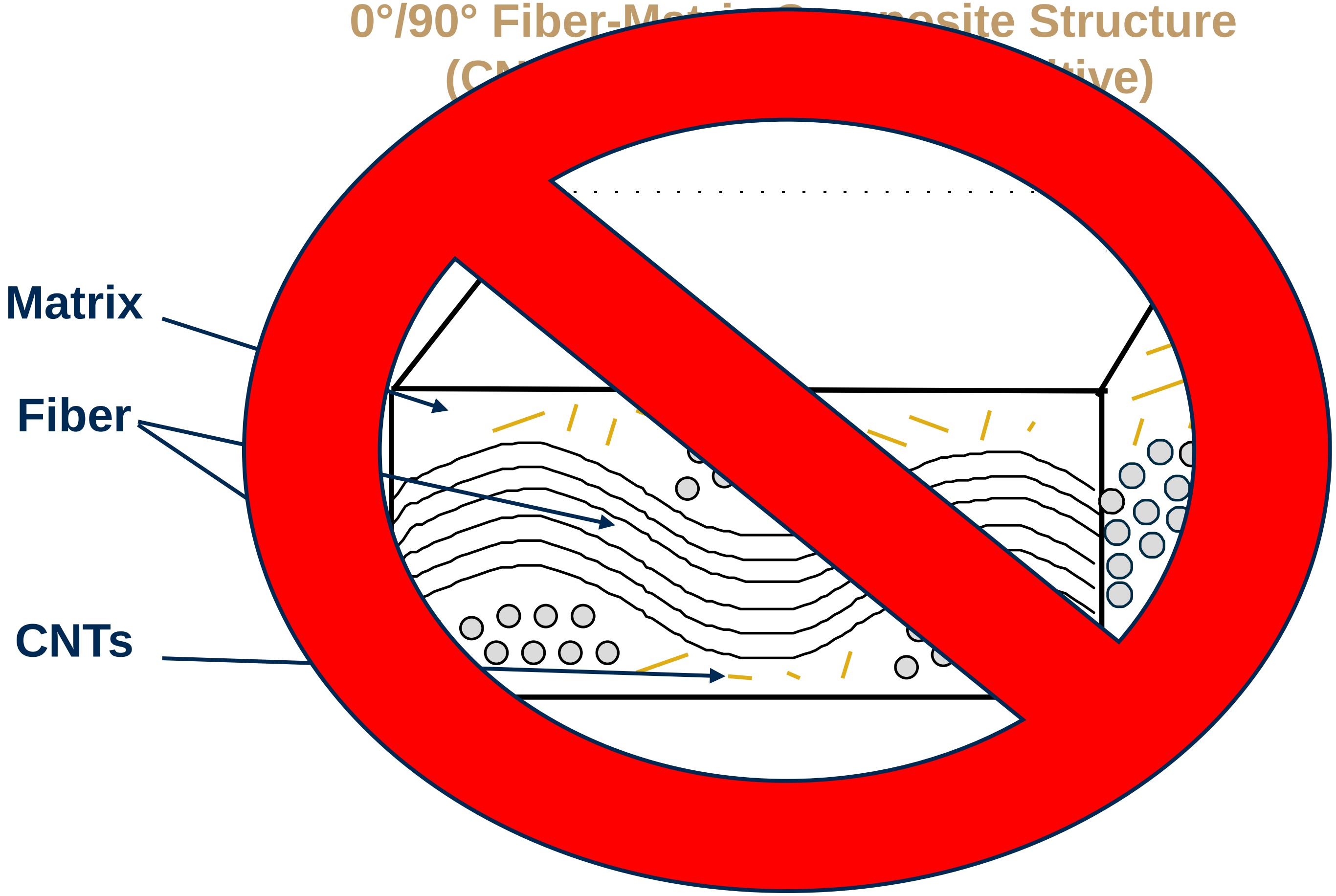


- **Functionalized Fabrics**
  - **Quartz / Basalt / Carbon Fiber Fabrics**
  - **Superior thermal properties**
  - **Electrically conductive**
  - **Tremendous Strength and formability**
  - **Monolithic / Multifunctional Materials**
  - **Grow CNTs on fabrics to increase absorption of thermal (IR) and/or electrical (RADAR) energy.**

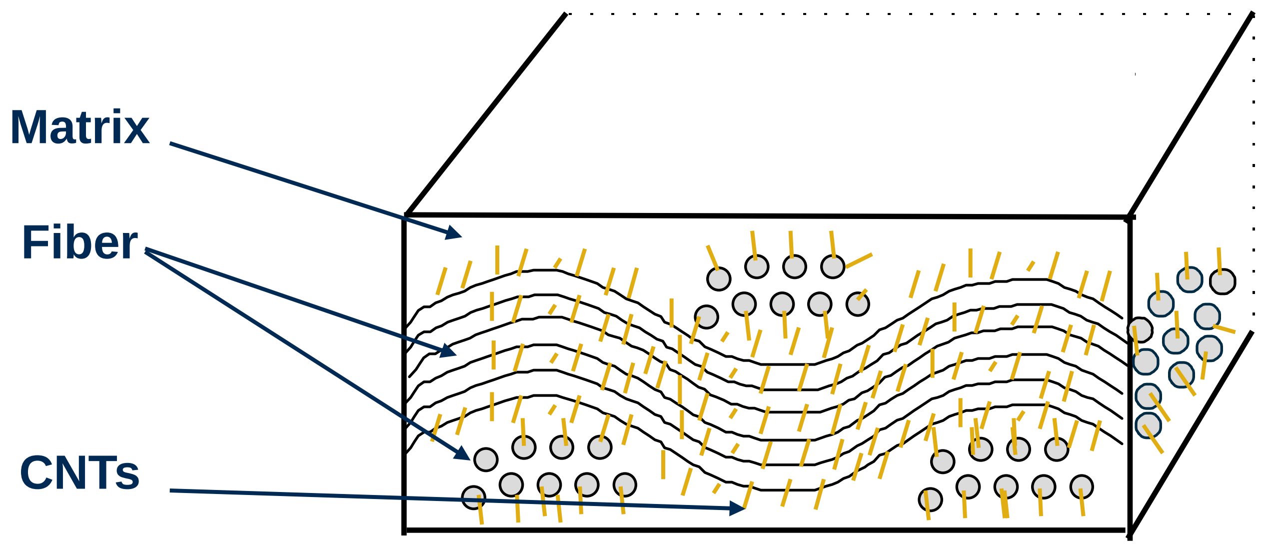
0°/90° Fiber-Matrix Composite Structure (CNTs incorporated as Additive)



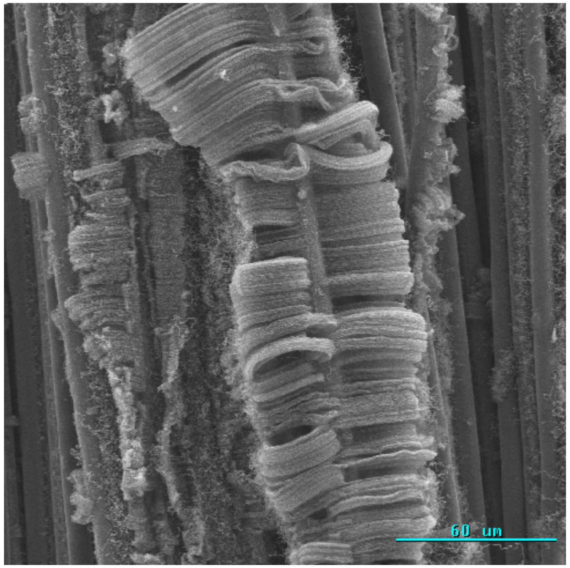
0°/90° Fiber-M... Composite Structure (CN... ...tive)

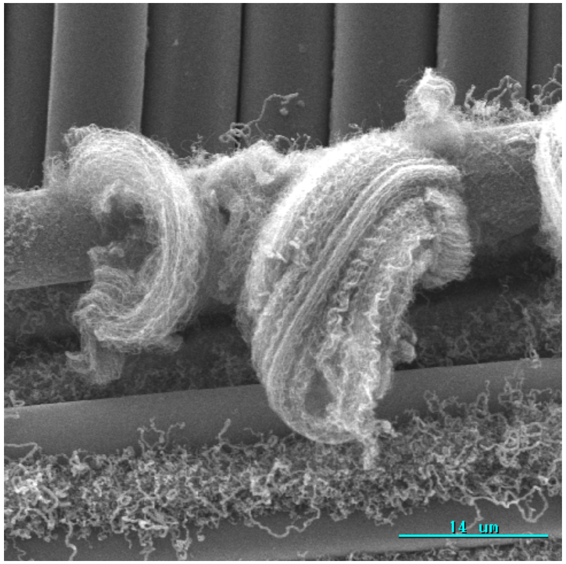


0°/90° Fiber-Matrix Composite Structure (CNTs "grown" on reinforcing fabric)

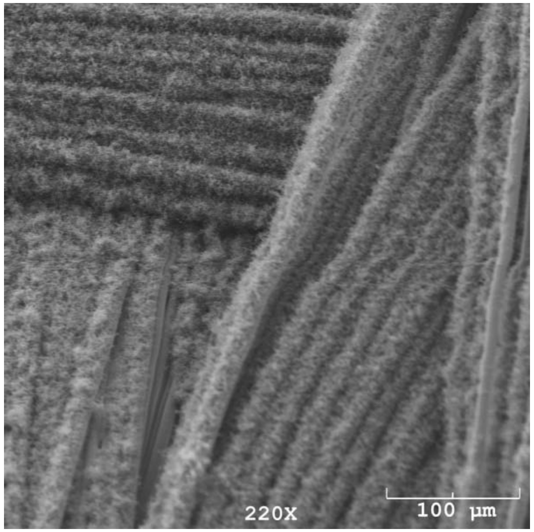


- **Liquid-Based Catalyst**
  - **Alumina-supported Fe nanopowder**
  - **Non-uniform coverage (nooks/crannies)**



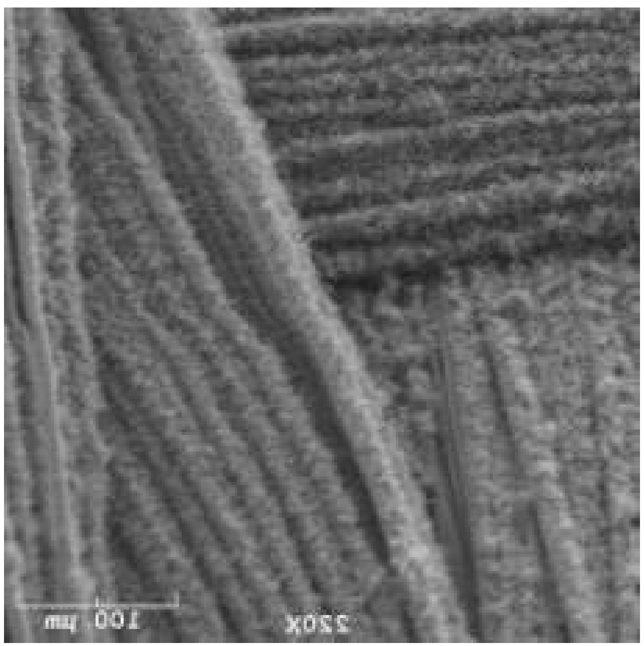


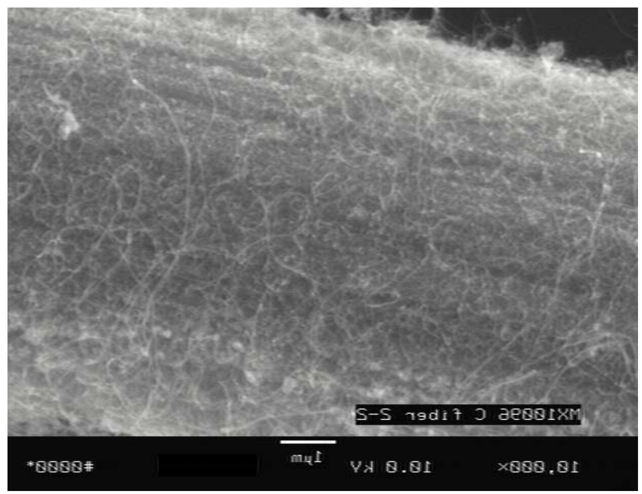
- **Thermal / e-beam evaporated**
    - **Fe and Ni**
    - **Dual-sided**

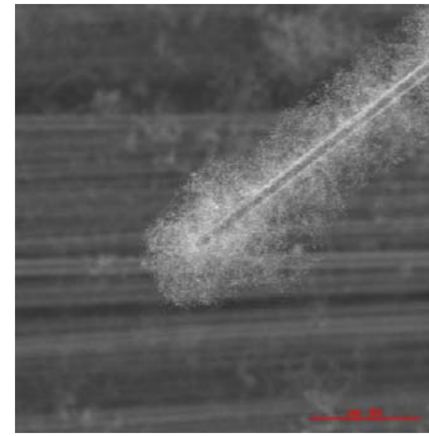


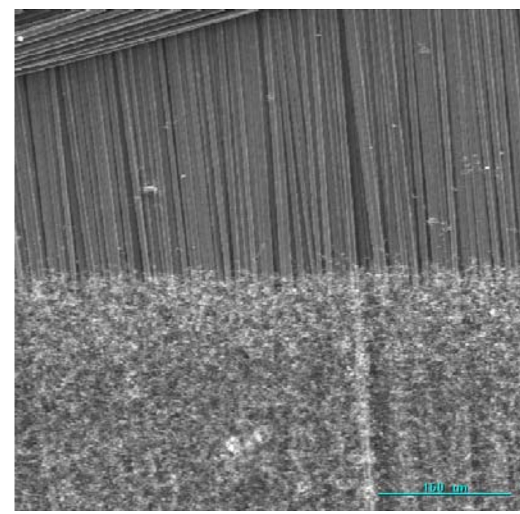
Functionalized Fabrics

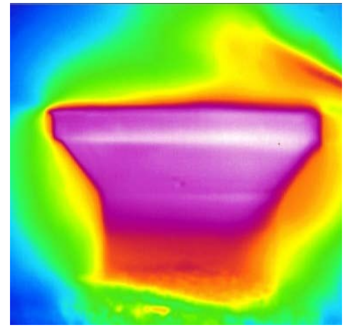
- CNTs on
  - C fabrics (T-300 from Cytek)



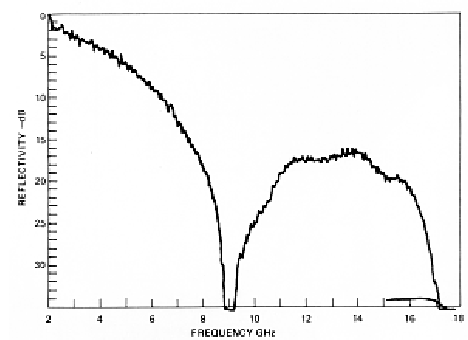




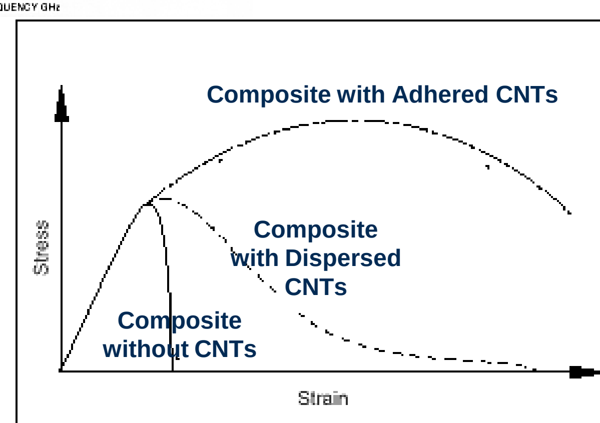




- **Thermal Absorption**



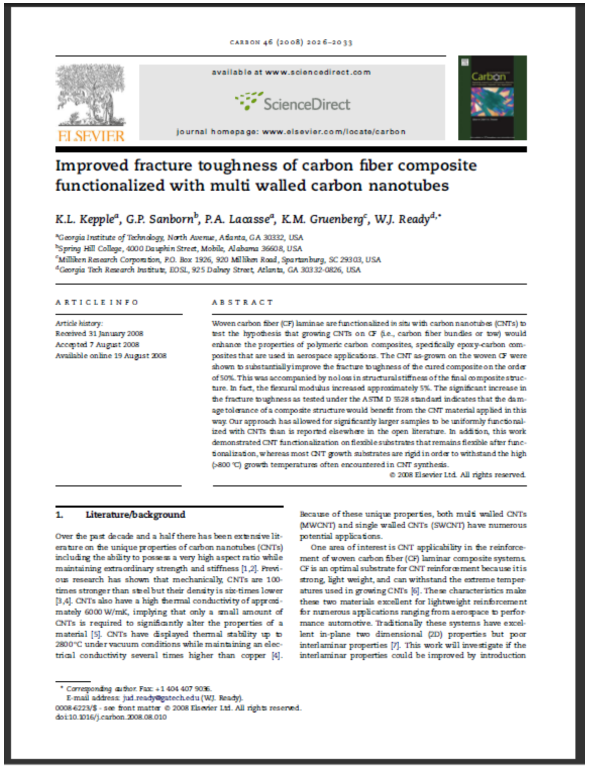
- **Microwave Attenuation**



- **Mechanical Toughening & Strengthening**

Functionalized Fabrics

- CNTs on
  - C fabrics
  - ASTM D 5528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Improved fracture toughness of carbon fiber composite functionalized with multi walled carbon nanotubes

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ABSTRACT

Woven carbon fiber (CF) laminae are functionalized in situ with carbon nanotubes (CNTs) to test the hypothesis that growing CNTs on CF (i.e., carbon fiber bundles or tow) would enhance the properties of polymeric carbon composites, specifically epoxy-carbon composites that are used in aerospace applications. The CNT as-grown on the woven CF were shown to substantially improve the fracture toughness of the cured composite on the order of 50%. This was accompanied by no loss in structural stiffness of the final composite structure. In fact, the flexural modulus increased approximately 5%. The significant increase in the fracture toughness as tested under the ASTM D 5528 standard indicates that the damage tolerance of a composite structure would benefit from the CNT material applied in this way. Our approach has allowed for significantly larger samples to be uniformly functionalized with CNTs than is reported elsewhere in the open literature. In addition, this work demonstrated CNT functionalization on flexible substrates that remains flexible after functionalization, whereas most CNT growth substrates are rigid in order to withstand the high (>800 °C) growth temperatures often encountered in CNT synthesis.

1. Literature/background

Over the past decade and a half there has been extensive literature on the unique properties of carbon nanotubes (CNTs) including the ability to possess a very high aspect ratio while maintaining extraordinary strength and stiffness [1,2]. Previous research has shown that mechanically, CNTs are 100-times stronger than steel but their density is six-times lower [3,4]. CNTs also have a high thermal conductivity of approximately 6000 W/mK, implying that only a small amount of CNTs is required to significantly alter the properties of a material [5]. CNTs have displayed thermal stability up to 2800 °C under vacuum conditions while maintaining an electrical conductivity several times higher than copper [4]. Because of these unique properties, both multi walled CNTs (MWCNT) and single walled CNTs (SWCNT) have numerous potential applications.

One area of interest is CNT applicability in the reinforcement of woven carbon fiber (CF) laminar composite systems. CF is an optimal substrate for CNT reinforcement because it is strong, light weight, and can withstand the extreme temperatures used in growing CNTs [6]. These characteristics make these two materials excellent for lightweight reinforcement for numerous applications ranging from aerospace to performance automotive. Traditionally these systems have excellent in-plane two dimensional (2D) properties but poor interlaminar properties [7]. This work will investigate if the interlaminar properties could be improved by introduction

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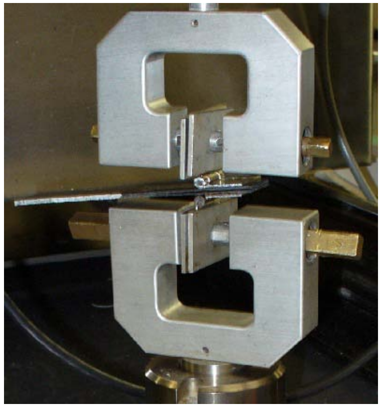
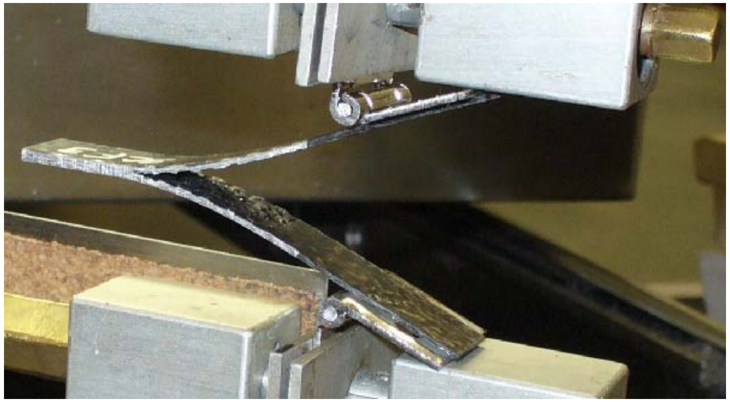
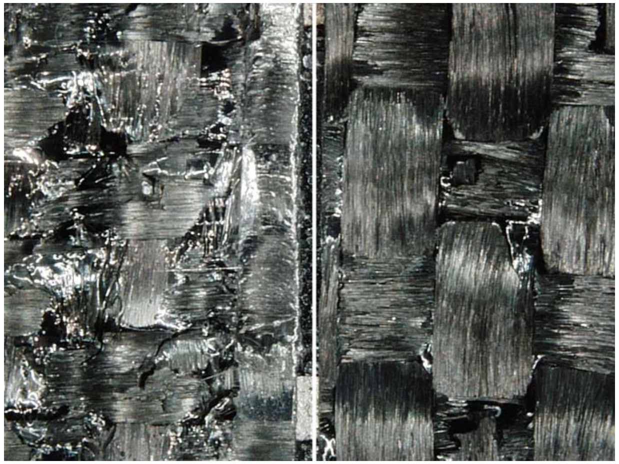
0008-6223/$ - see front matter
doi:10.1016/j.carbon.2008.08.010



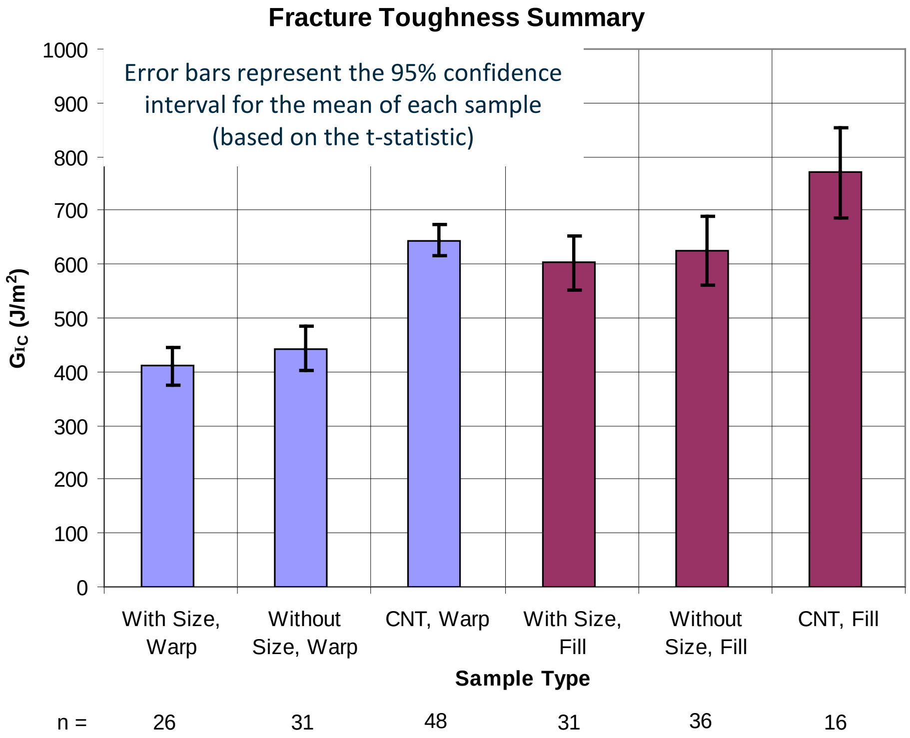


Functionalized Fabrics

- CNTs on
  - C fabrics
  - ASTM D 5528



No CNT CNT



Functionalized Fabrics

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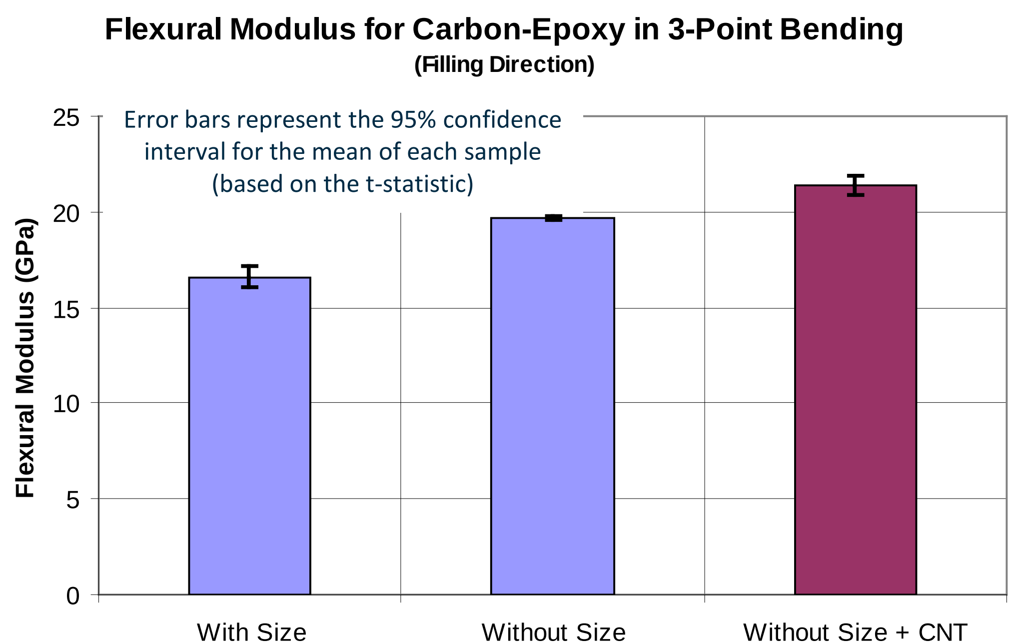
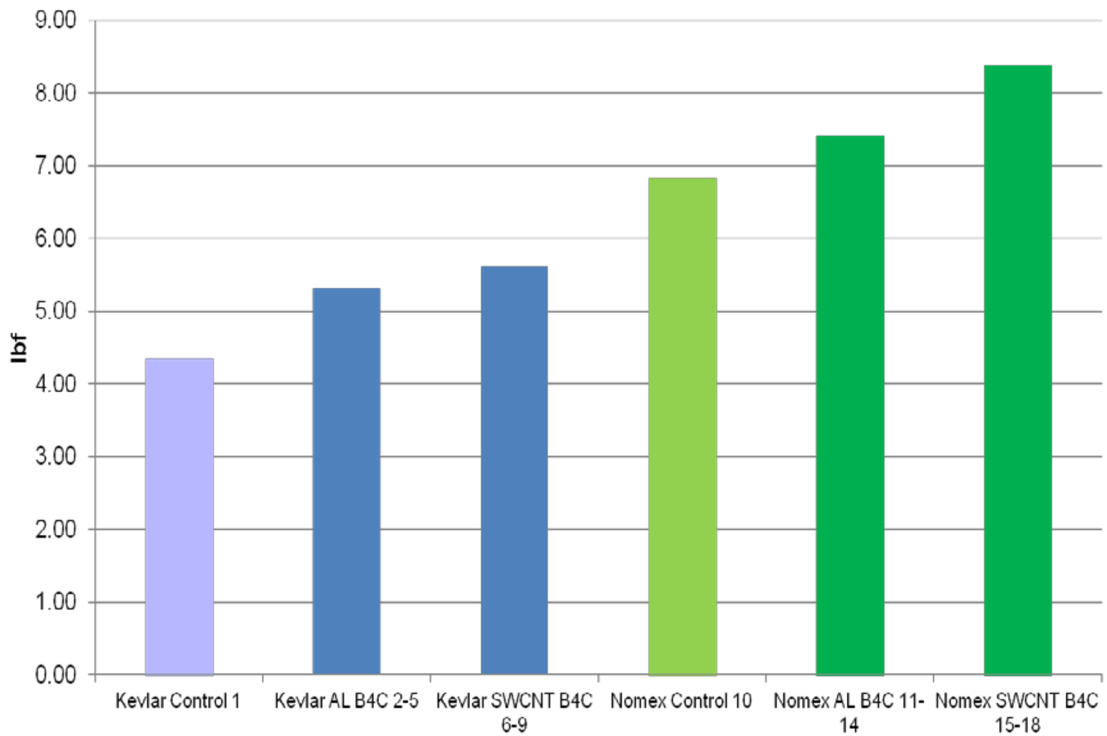


n = 12 (ea.)

- Modified fabrics tested according to ASTM F1342-05 Standard Test Method for Protective Clothing Material Resistance to Puncture
- Results show improved puncture resistance for both fabrics
  - CNT+B_4C yielded highest improvement

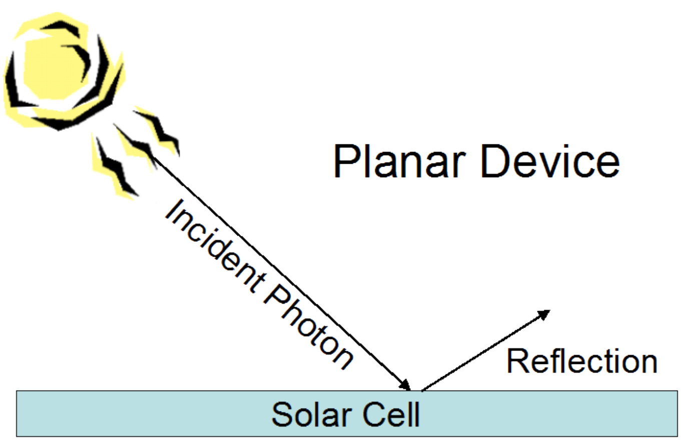


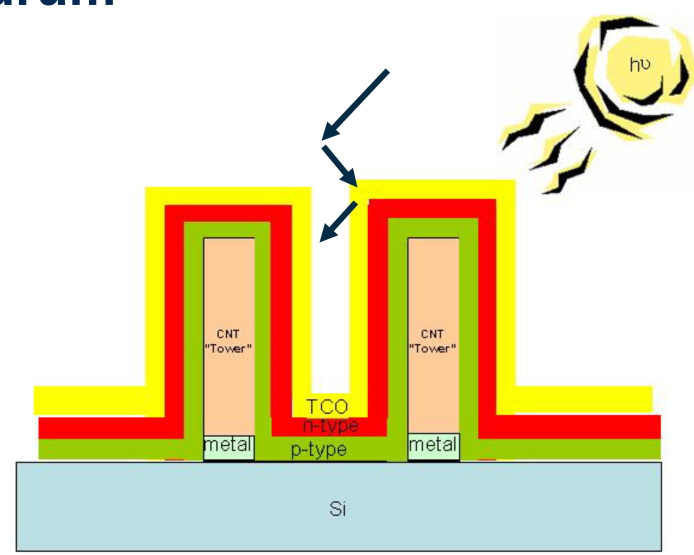
Future Research Directions

- **Additional ASTM-tests**
  - **ASTM-D-6484 – Open Hole Compression**
  - **ASTM-D-7136 & -7137 – Compression after Impact**
  - **ASTM-D-2344 – Short Beam Shear Strength**
  - **ASTM-D-7078 & -5379 – V-notched Rail Shear**
  - **ASTM-D-6641 & -3410 – Wyoming Combined Loading Compression**
- **Thermal Testing**
- **EMI Testing**
- **RADAR Absorption**

Light trapping 3D Photovoltaics

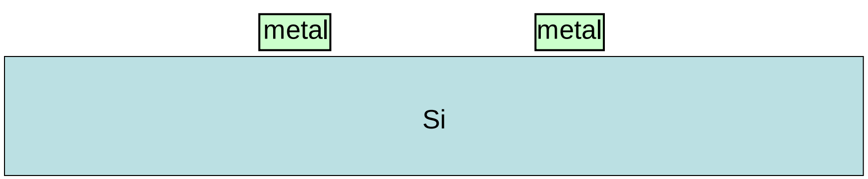
- Light Trapping= more absorbance
- Thinner layers = less recombination
- “orthogonalize” absorption and carrier extraction
- Solves “thick-thin” conundrum





CNT-Based Approach

- **Pattern generated on Si substrate via photolithography**
- **Metal catalyst (Fe) applied**
- **Lift-off photoresist to leave only patterned catalyst**



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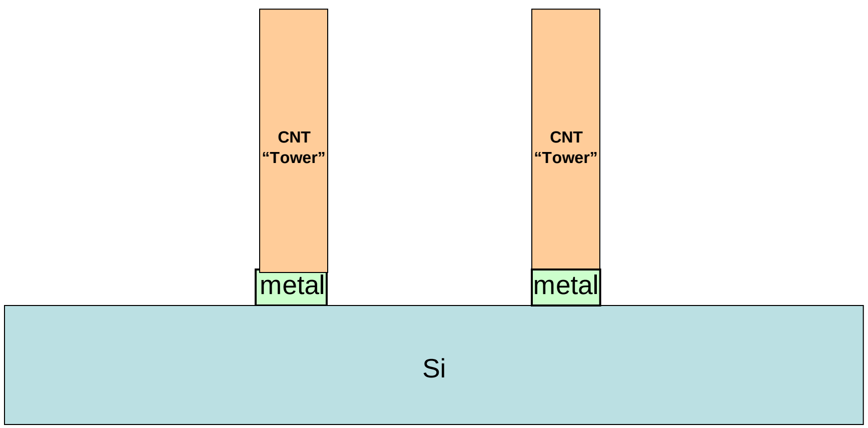

- Pattern generated on Si substrate via photolithography
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- CNT towers are formed in Chemical Vapor Deposition (CVD) furnace (~720°C; 20 min.)

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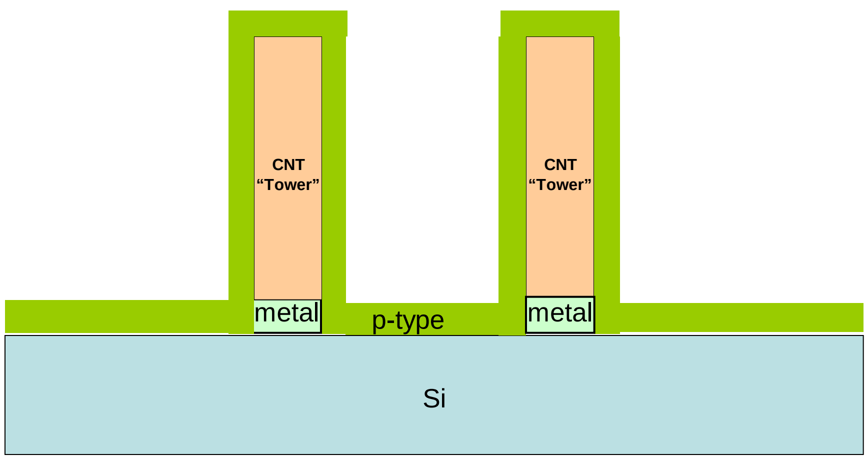

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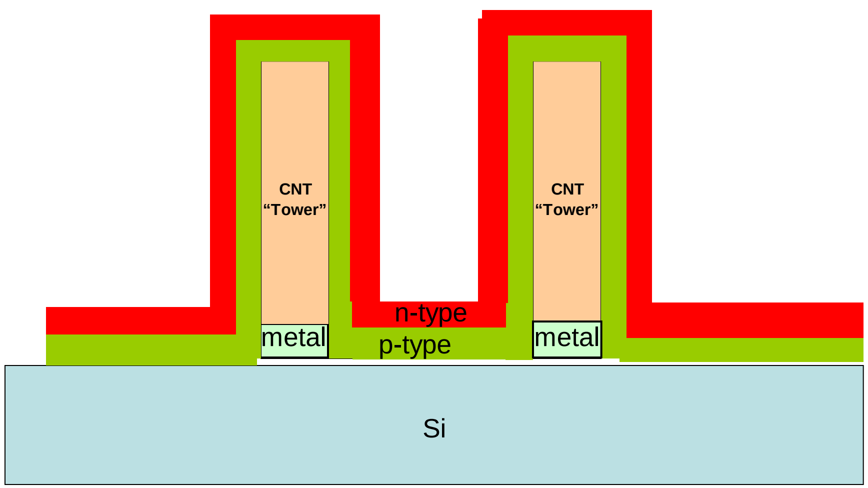

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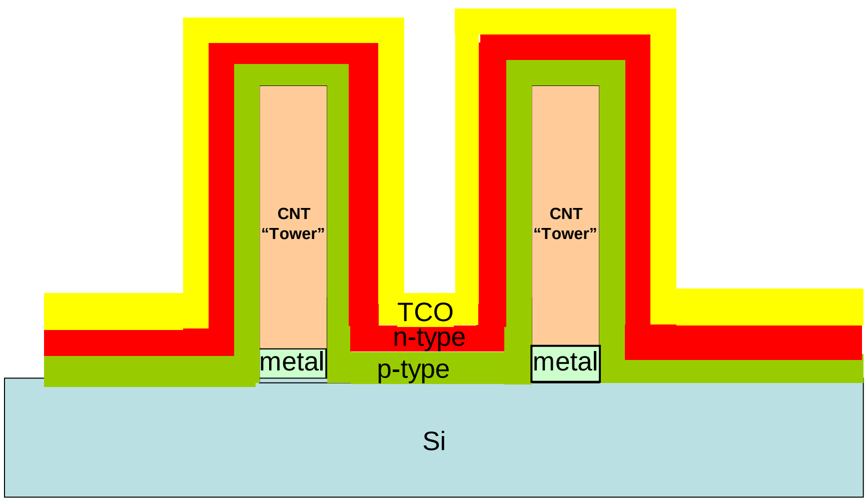
- n-type material (CdS) applied via MBE or CBD

CNT-Based Approach



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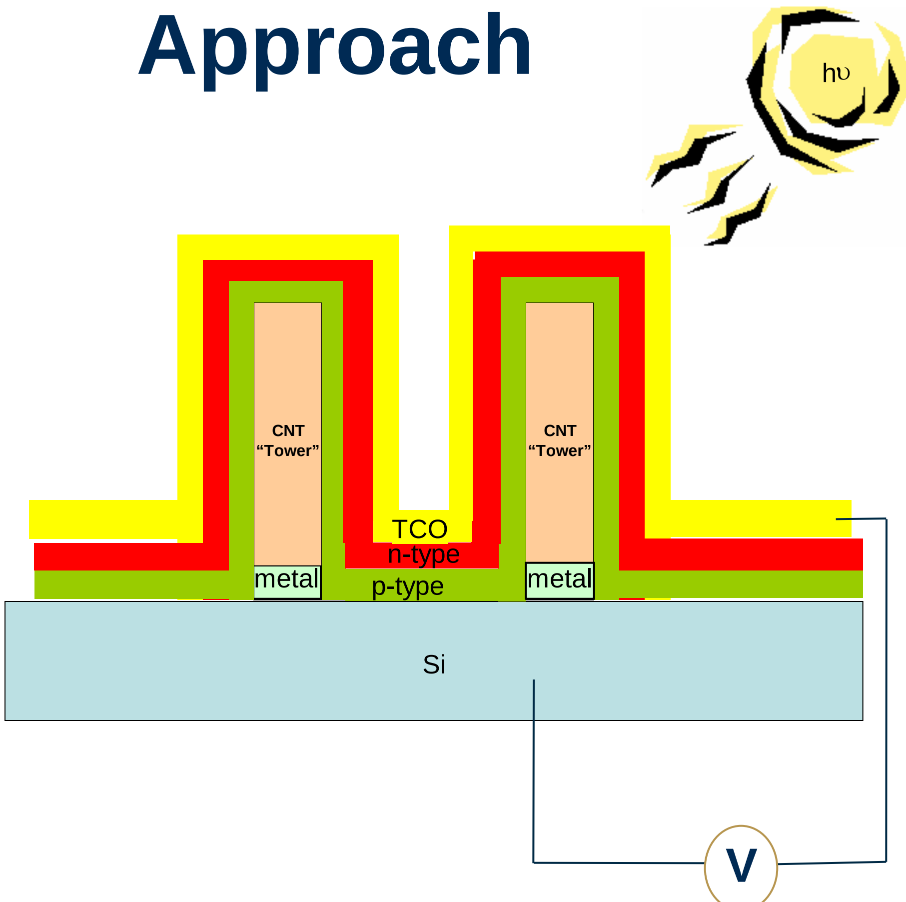
- n-type material (CdS) applied via MBE or CBD
- Transparent Conductive Oxide applied via ion assisted deposition (IAD)

CNT-Based Approach



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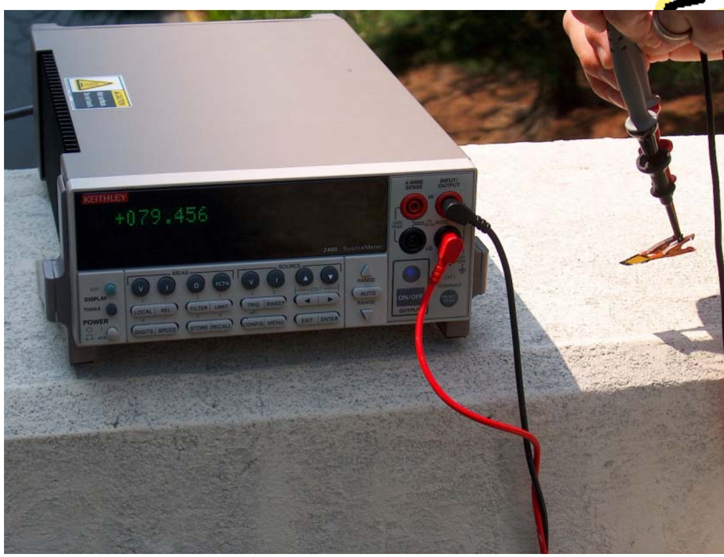
CNT-Based Approach



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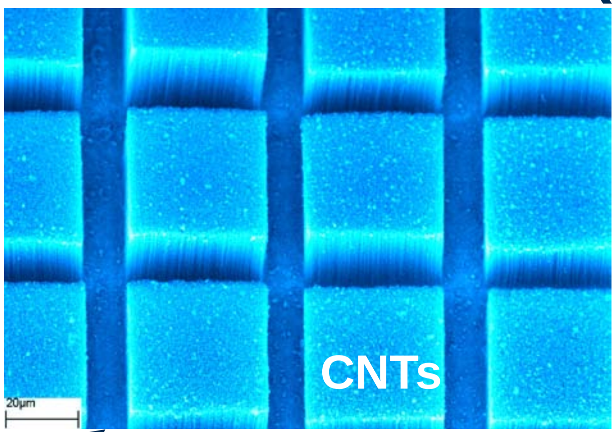
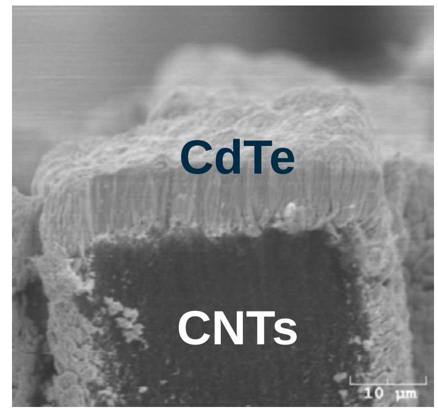
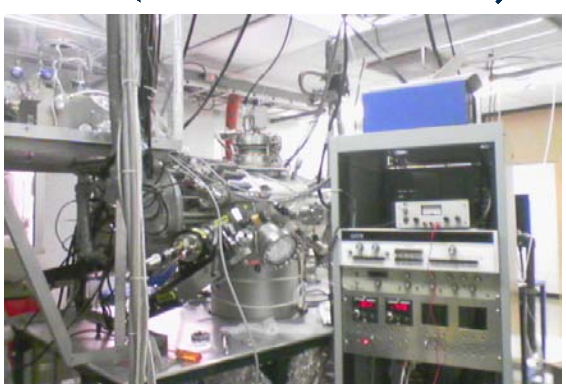
- **n-type material (CdS) applied via MBE**
- **Transparent Conductive Oxide applied via ion assisted deposition (IAD)**

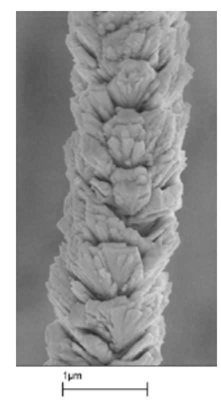
Molecular Beam Epitaxy for CdTe and CdS deposition (p/n junction)

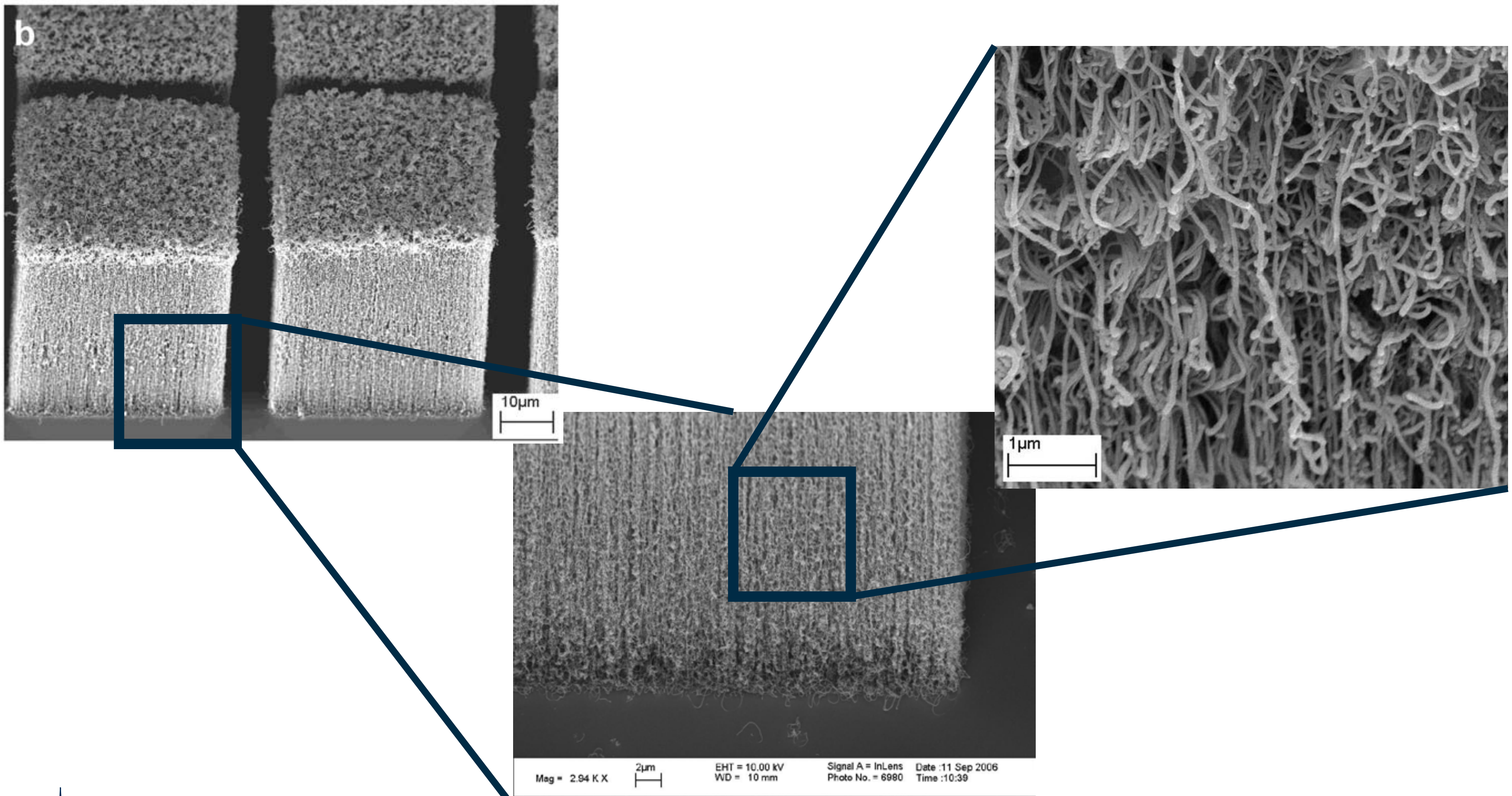


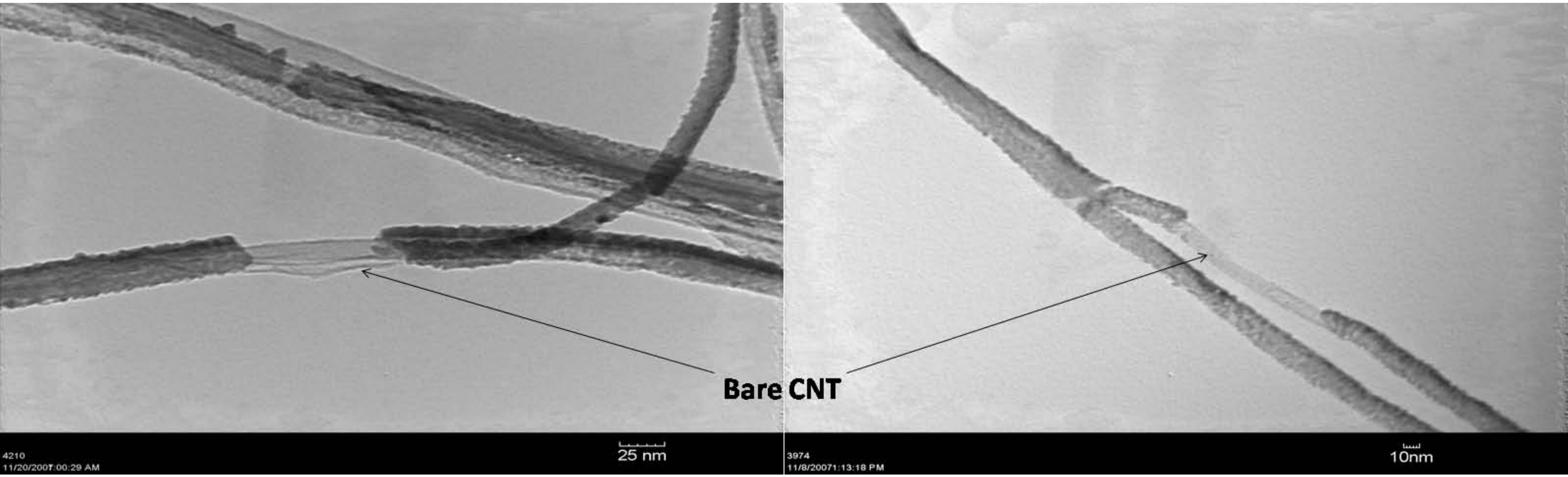
Si substrate



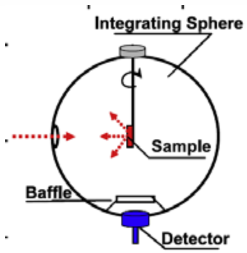


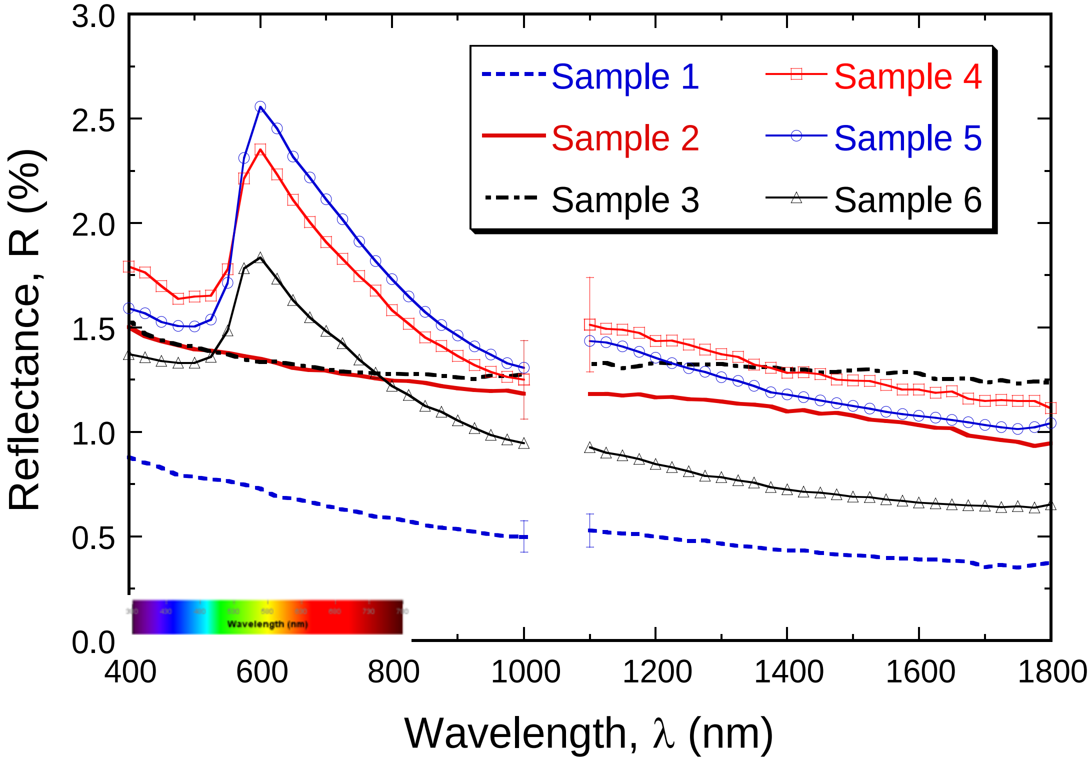


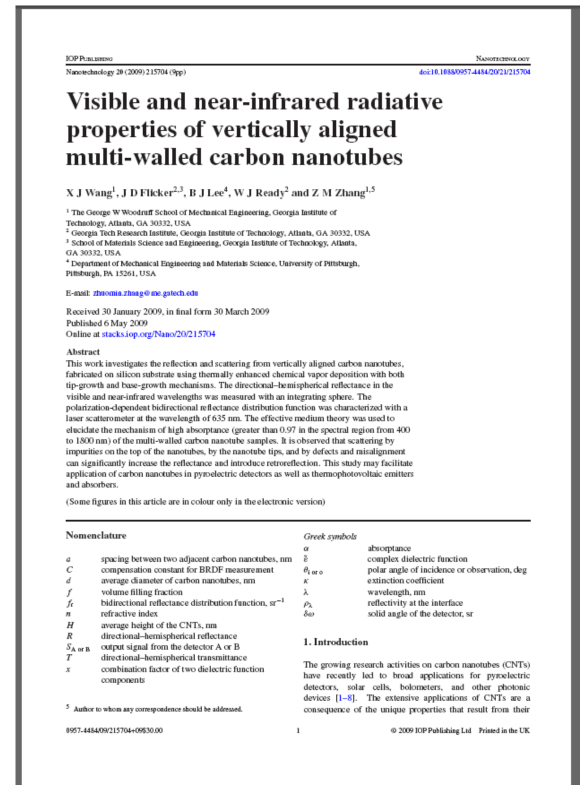

b
10µm
1µm
Mag = 2.94 K X
2µm
EHT = 10.00 kV
WD = 10 mm
Signal A = InLens
Photo No. = 6980
Date :11 Sep 2006
Time :10:39


Bare CNT
4210
25 nm
3974
11/8/20071:13:18 PM
10nm

Light Reflection







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Visible and near-infrared radiative properties of vertically aligned multi-walled carbon nanotubes

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Abstract
This work investigates the reflection and scattering from vertically aligned carbon nanotubes, fabricated on silicon substrate using thermally enhanced chemical vapor deposition with both tip-growth and base-growth mechanisms. The directional–hemispherical reflectance in the visible and near-infrared wavelengths was measured with an integrating sphere. The polarization-dependent bidirectional reflectance distribution function was characterized with a laser scatterometer at the wavelength of 635 nm. The effective medium theory was used to elucidate the mechanism of high absorptance (greater than 0.97 in the spectral region from 400 to 1800 nm) of the multi-walled carbon nanotube samples. It is observed that scattering by impurities on the top of the nanotubes, by the nanotube tips, and by defects and misalignment can significantly increase the reflectance and introduce retroreflection. This study may facilitate application of carbon nanotubes in pyroelectric detectors as well as thermophotovoltaic emitters and absorbers.

(Some figures in this article are in colour only in the electronic version)

Nomenclature

a	spacing between two adjacent carbon nanotubes, nm
C	compensation constant for BRDF measurement
d	average diameter of carbon nanotubes, nm
f	volume filling fraction
f_r	bidirectional reflectance distribution function, sr^{-1}
n	refractive index
H	average height of the CNTs, nm
R	directional–hemispherical reflectance
$S_{A \text{ or } B}$	output signal from the detector A or B
T	directional–hemispherical transmittance
x	combination factor of two dielectric function components

Greek symbols

α	absorptance
$\tilde{\varepsilon}$	complex dielectric function
$\theta_{i \text{ or } o}$	polar angle of incidence or observation, deg
κ	extinction coefficient
λ	wavelength, nm
ρ_λ	reflectivity at the interface
$\delta\omega$	solid angle of the detector, sr

1. Introduction

The growing research activities on carbon nanotubes (CNTs) have recently led to broad applications for pyroelectric detectors, solar cells, bolometers, and other photonic devices [1–8]. The extensive applications of CNTs are a consequence of the unique properties that result from their

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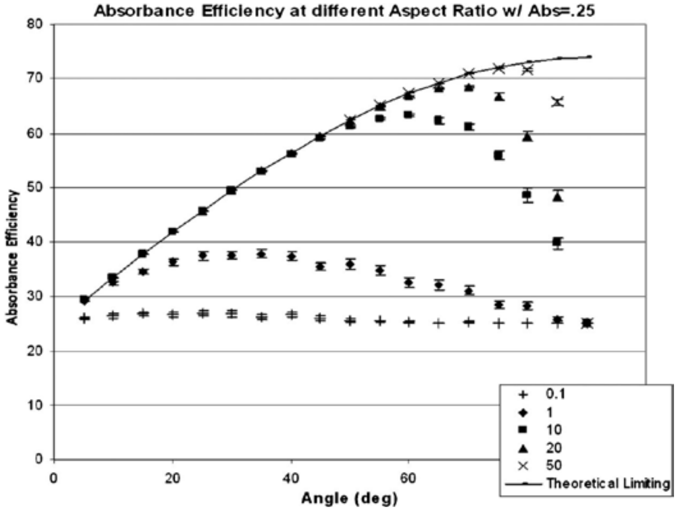
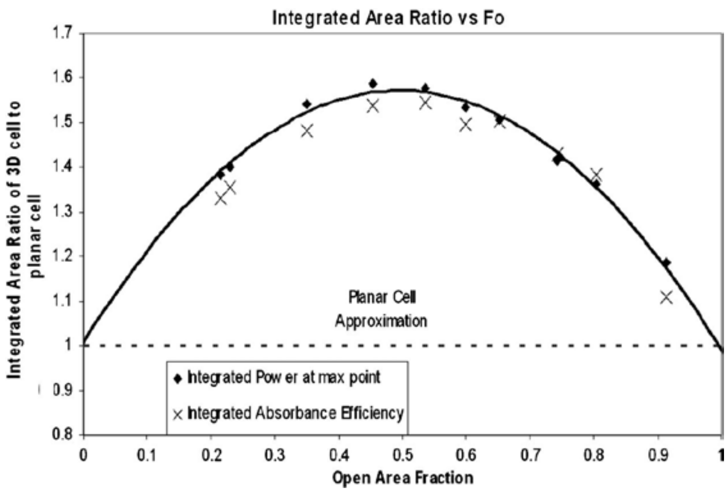
Modeling





JOURNAL OF APPLIED PHYSICS 103, 113110 (2008)

Simulations of absorbance efficiency and power production of three dimensional tower arrays for use in photovoltaics

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The production of cheap energy from the sun will be a major research objective in the coming years. Major strides must be made in solar cell efficiency, including increasing absorbance efficiency of a cell by etching or texturing. In order to increase the absorbance efficiency of solar cells, we have developed a three-dimensional solar cell structure by depositing a cadmium telluride thin film overtop carbon nanotube towers. These towers act as both a scaffolding and an electrical interconnect. Multiple photon interactions as they reflect between these towers increase the absorption efficiency. We have developed a theoretical model and computer simulation to maximize the number of photon interactions due to the geometrical characteristics of the system (aspect ratio, spacing, size, shape, etc.). Simulated modeling has shown that by optimization of parameters, a three-dimensional cell can obtain up to a 300% increase in power production over traditional cells. © 2008 American Institute of Physics. [DOI: 10.1063/1.2937242]

INTRODUCTION

Of the many drivers for a change to a renewable primary power source, arguably the most disastrous and menacing are the environmental needs for carbon-free power generation. According to work done by Hoffert *et al.* based on the International Panel on Climate Change (IPCC), in order to stabilize anthropogenic levels of CO_2 from fossil fuel use by 2035, the world must produce at least 10 TW of carbon-free power.[1] However, as is apparent to every economist and politician, the drive for a clean, renewable power will not happen purely due to subsidies and the only hope for reaching the 10 TW mark is for a free market sustained push for renewable energies. This will only happen if the price per watt of solar cells can compete with fossil fuels. In order for photovoltaics (PVs) to decrease from the \$0.3–0.5/kW h range currently to the \$0.06–0.08/kW h range of conventional fossil fuels, the development of cheap solar cells on the order of \$10/m^2 is needed. PVs need to be easy to manufacture, have no expensive tracking machinery, and have a high efficiency.[2]

One of the technologies with the most promise to provide power from the sun is organic solar cells, which can be produced much more cheaply and safely than traditional organic photovoltaics.[3] A number of groups have demonstrated the use of carbon nanotubes (CNTs) as an electron acceptor molecule in organic solar cells[4–8] and the use of vertically aligned CNTs produced through large-scale chemical vapor deposition[9,10] (CVD) has been proposed for use in organic solar cells.[11]

Previous work by the Ready group has used vertically aligned CNT tower arrays to create inorganic solar cells.[12] These three dimensional (3D) cells are composed of regularly spaced tower composed of vertically aligned CNTs grown by CVD [Fig. 1(a)]. Molecular beam epitaxy is used to deposit a CdTe, CdS heterojunction with an indium tin oxide collection electrode [Fig. 1(b)]. Due to reflections off the tower faces and multiple chances for photon absorption, these cells show a high current density and increased power production at off-normal angles. Although 3D cells of this type have been shown to increase the power produced at off-normal angles, it is not quantitatively known how the geometrical aspects of the array of towers will affect the power produced and what geometrical parameters are needed in order to maximize the produced power. This paper develops a quantitative theory of the absorption efficiency and power production in 3D CNT based photovoltaic cells, and simulations are carried out in order to optimize the geometrical parameters of the system.

THEORETICAL DETERMINATION OF ABSORBANCE EFFICIENCY

A first-order theoretical determination of absorbance efficiency (η_{abs}), the percentage of insolation absorbed, is greatly simplified with a number of assumptions. It is assumed that the model cell is infinite in extent and, therefore, all photons, except those traveling perpendicular to the cell surface, will impinge the surface. It is also assumed that all surfaces are nonrough and that specular reflection occurs at each impingement. Finally, it is assumed that at each impingement, a photon of light is either reflected or absorbed and that the characteristic dimensions of the topological features are significantly larger than the absorption distance of the material, so that transmission through features without absorption may be ignored.

For nanoscale features with multilayers possessing small absorption coefficients α, this assumption readily breaks down and any complete theory must take into account transmission through features in addition to absorption and reflec-

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0021-8979/2008/103(11)/113110/10/\$23.00

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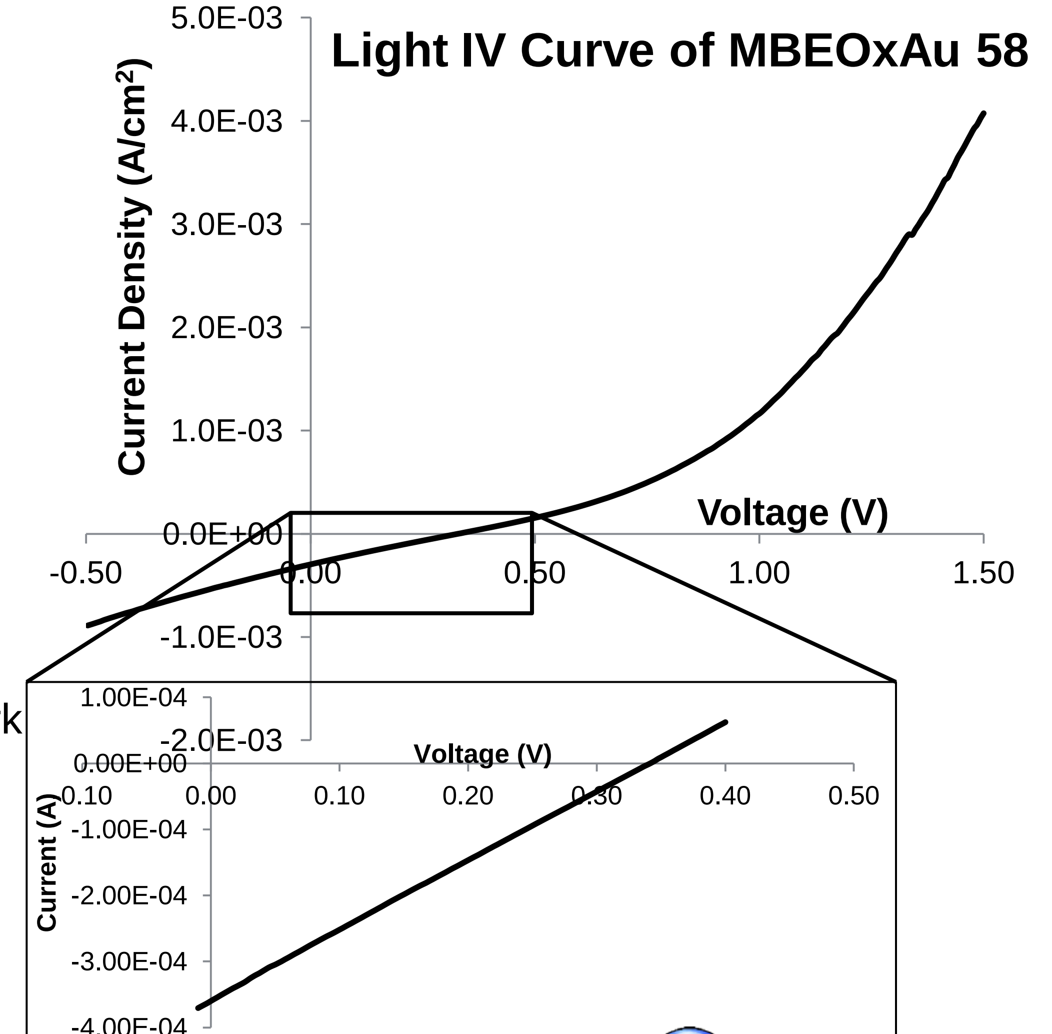
Device Fabrication

- R_{sh} and R_s values of cell comparable to NREL
- See good curvature of IV curve
- However, photocurrent gain is not large enough to catch curvature in 4th quadrant
- Other postpocessing methods, such as $CdCl_2$ annealing, usually increase I_{sc} in CdTe/CdS cells
- No $CdCl_2$ process has been found to work on 3DCNTPV cells yet



Summary

1. Developed a complete theoretical model of the 3DCNTPV cell and introduced two new paramaters, η_{3D} and Γ

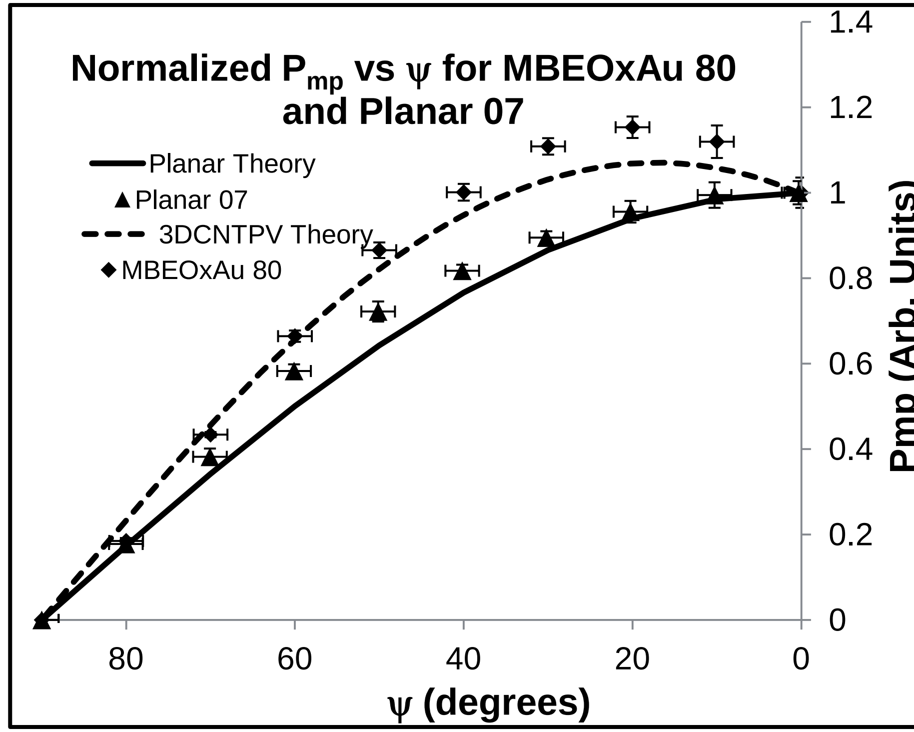
2. Developed a simple-cost effective way to texture thin film solar cells using a “bottom up” substrate-configuration approach using VACNTs as a textured back contact

3. Created working proof-of-concept devices using the 3DCNTPV structure

4. Increased device I_{sc} by an order of magnitude and V_{oc} by 300% through processing and device architecture changes

5. Reduced shunting and induced IV curvature through the use of a high resistance transparent layer

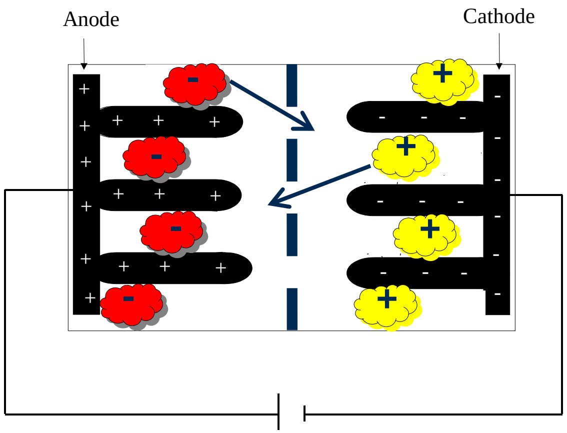
6. Confirmed theoretical model with experimental data of power output vs. solar flux incident angle



Future Work

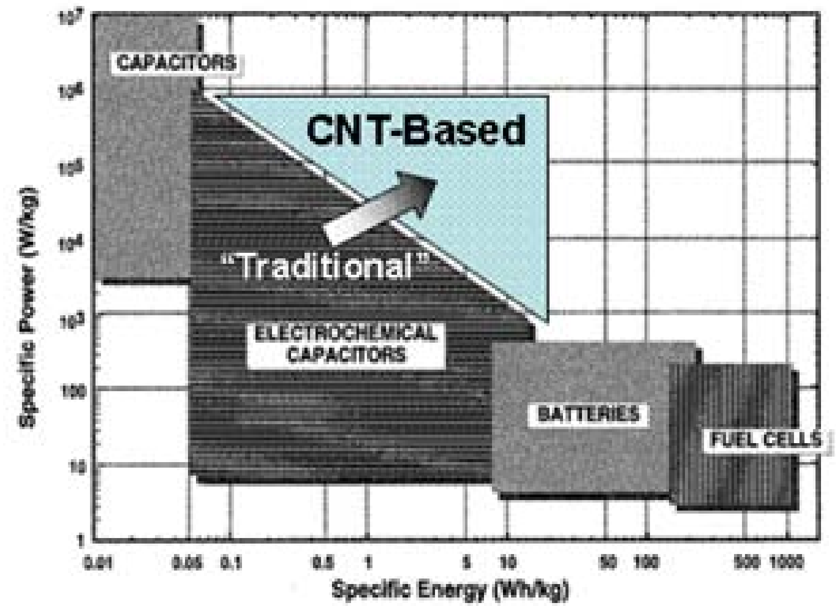
- Licensed for commercialization by Bloo Solar
- Alternate PV materials (vs. CdTe/CdS)
  - a-Si
  - CZTS
  - CIGS

Supercapacitors



$$C = \frac{\varepsilon_o \cdot \varepsilon_r \cdot A_E}{d}$$

$$Energy\_Stored = \frac{1}{2} C V^2$$

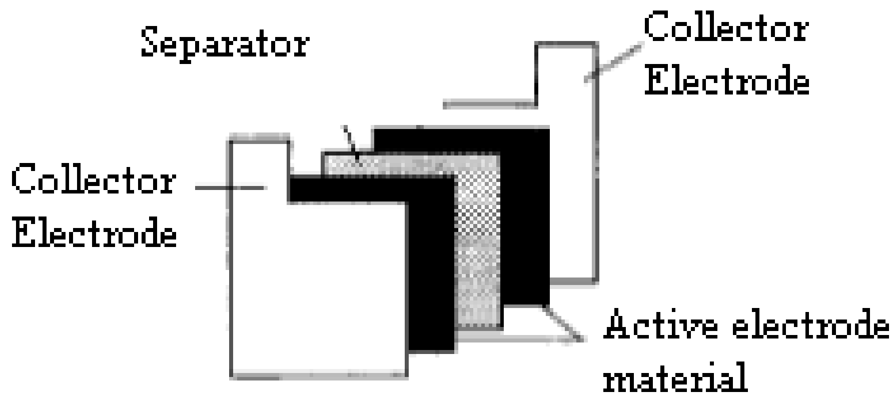


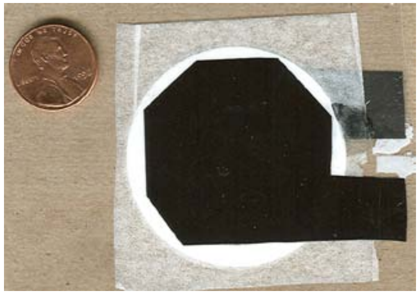
Carbon Nanotubes

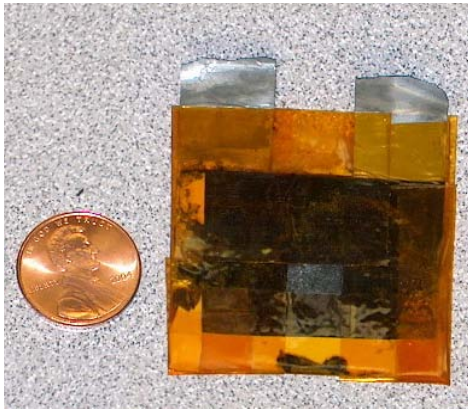
- High surface area
- Percolated network
- Coat/functionalize CNTs or alter the electrolyte to adjust power/energy requirements

ECDL Construction

- Active electrode material in contact with a current collector
  - Multiple techniques:
    1. CNTs blended into paste with binders and other constituents
    2. Grown in situ via CVD on electrode
    3. Vacuum Filtration + Thermal Evap
- Alter Separator membrane
  - allows transport of ions, but is electrically insulating
- Alter Electrolyte
  - High Voltage Stabilty
  - High Conductivity
  - Low Viscocity
  - Low Cost





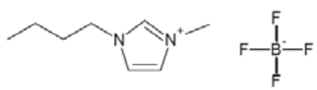


Research Going Forward

- **Improve Electrolyte**

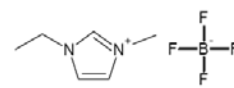
#5

IUPAC Name: **1-butyl-3-methylimidazolium tetrafluoroborate**
Shorthand:
$[1\text{-Bu-3-MeIm}^+][BF_4^-]$
BMIMBF4
Formula: $C_8H_{15}BF_4N_2$
Molecular weight: 226.02
Melting point: < -50°C
Density (g/cm³ at 20°C): 1.21
Viscosity (mm²/s at 20°C): 120.00
Miscibility: water, acetonitrile
Merck/EMD Catalog Number: 491049
Alfa Aesar Catalog Number: L19087
Fisher Catalog Number: AC35421-0050
CAS No.: 174501-65-6



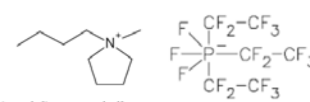
#7

IUPAC Name: **1-ethyl-3-methylimidazolium tetrafluoroborate**
Shorthand:
$[1\text{-Et-3-MeIm}^+][BF_4^-]$
EMIMBF4
Formula: $C_6H_{11}BF_4N2$
Molecular weight: 197.97
Melting point: 14°C
Density (g/cm³ at 20°C): 1.34
Viscosity (mm²/s at 20°C): 113.20
Miscibility: water, acetonitrile, hexane (partial)
Merck/EMD Catalog Number: 491037
Alfa Aesar Catalog Number: L19763
Fisher Catalog Number: NC9245825
CAS No.: 143314-16-3



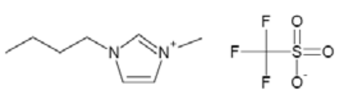
#9

IUPAC Name: **1-butyl-1-methylpyrrolidinium tris(pentafluoroethyl)trifluorophosphate**
Shorthand:
$[1\text{-Bu-1-MePy}^+][PF_3(C_2F_5)_3^-]$
BMPyFAP
Formula: $C_{15}H_{20}F_{18}NP$
Molecular weight: 587.27
Melting point: 4°C
Density (g/cm³ at 20°C): 1.59
Viscosity (mm²/s at 20°C): 184.90
Miscibility: isopropanol (partial), hexane (partial), acetonitrile
Merck/EMD Catalog Number: 491084
Alfa Aesar Catalog Number: Not in stock
Fisher Catalog Number: Not in stock
CAS No.: 851856-47-8



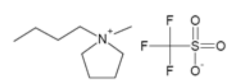
#6

IUPAC Name: **1-butyl-3-methylimidazolium trifluoromethansulfonate**
Shorthand:
$[1\text{-Bu-3-MeIm}^+][CF_3SO_3^-]$
BMIMCF3SO3
Formula: $C_9H_{15}F_3N_2O_3S$
Molecular weight: 288.29
Melting point: 17°C
Density (g/cm³ at 20°C): 1.30
Viscosity (mm²/s at 20°C): 88.60
Miscibility: water, isopropanol, acetonitrile
Merck/EMD Catalog Number: 491024
Alfa Aesar Catalog Number: L19765
Fisher Catalog Number: AC35679-0100
CAS No.: 174899-66-2



#8

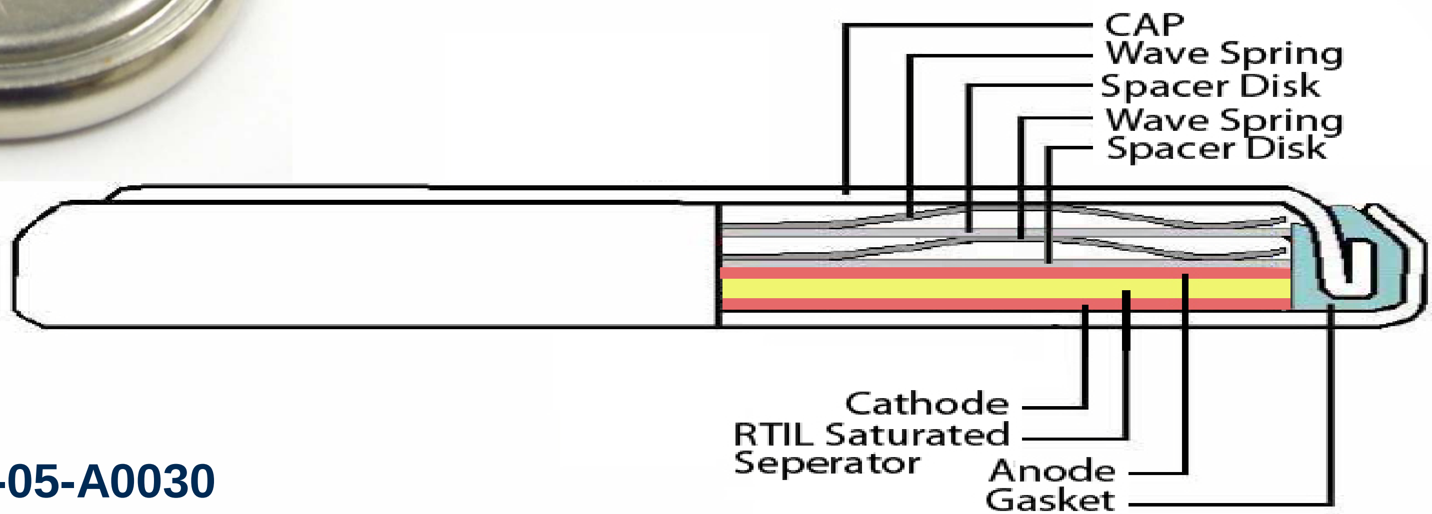
IUPAC Name: **1-butyl-1-methylpyrrolidinium trifluoromethanesulfonate**
Shorthand:
$[1\text{-Bu-1-MePy}^+][CF_3SO_3^-]$
BMPyOTF
Formula: $C_{10}H_{20}F_3NO_3S$
Molecular weight: 291.33
Melting point: 3°C
Density (g/cm³ at 20°C): 1.25
Viscosity (mm²/s at 20°C): 173.90
Miscibility: water, isopropanol, acetonitrile
Merck/EMD Catalog Number: 491029
Alfa Aesar Catalog Number: Not in stock
Fisher Catalog Number: Not in stock
CAS No.: 367522-96-1



ECDL Construction
3rd Generation – (show video!)

"CR2032" Coin Cells are capable of insertion into ARMY product.

Coin cell crimping ensures hermeticity and long life.



- W31P4Q-05-A0030

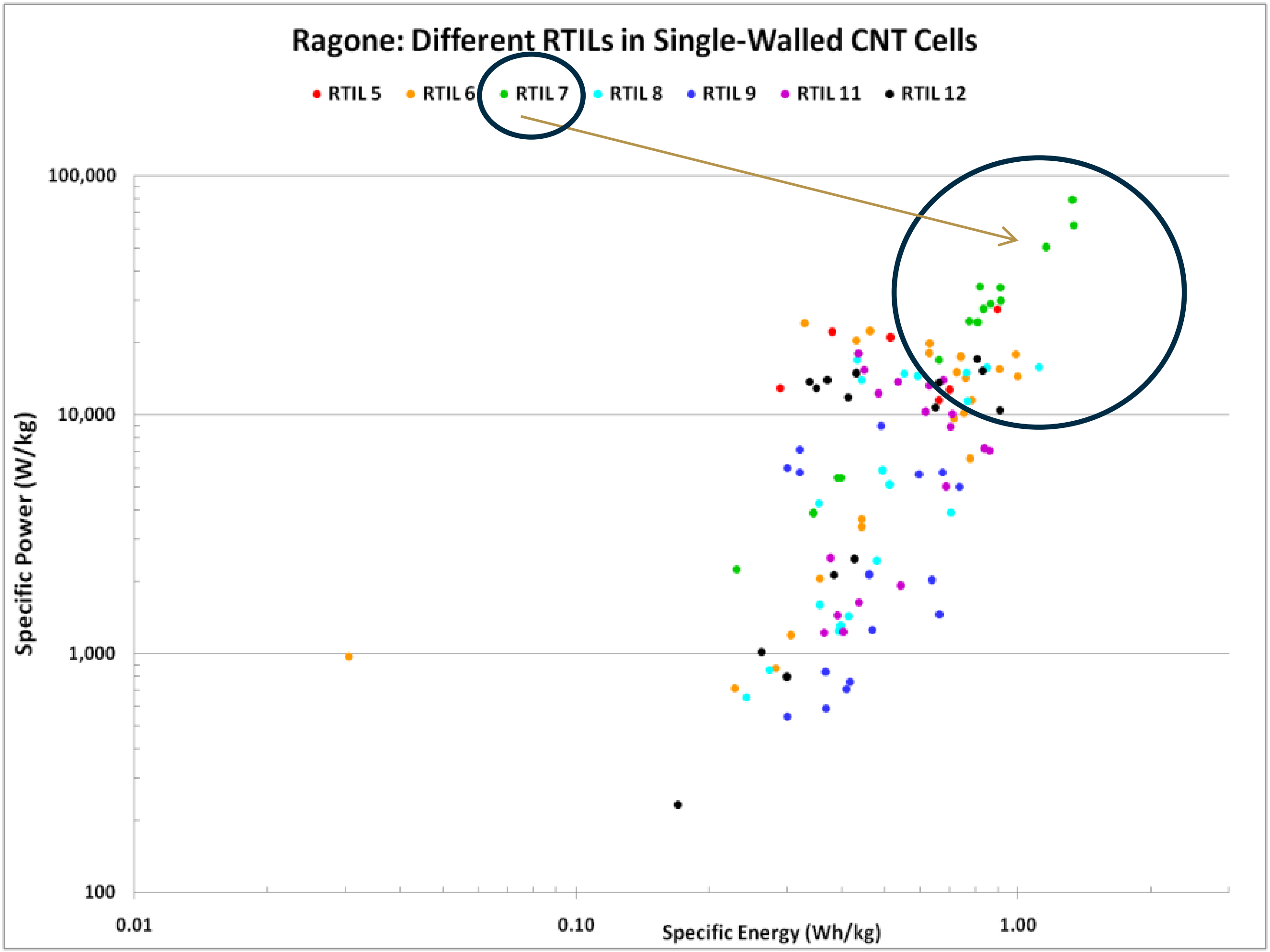
Electrical Testing

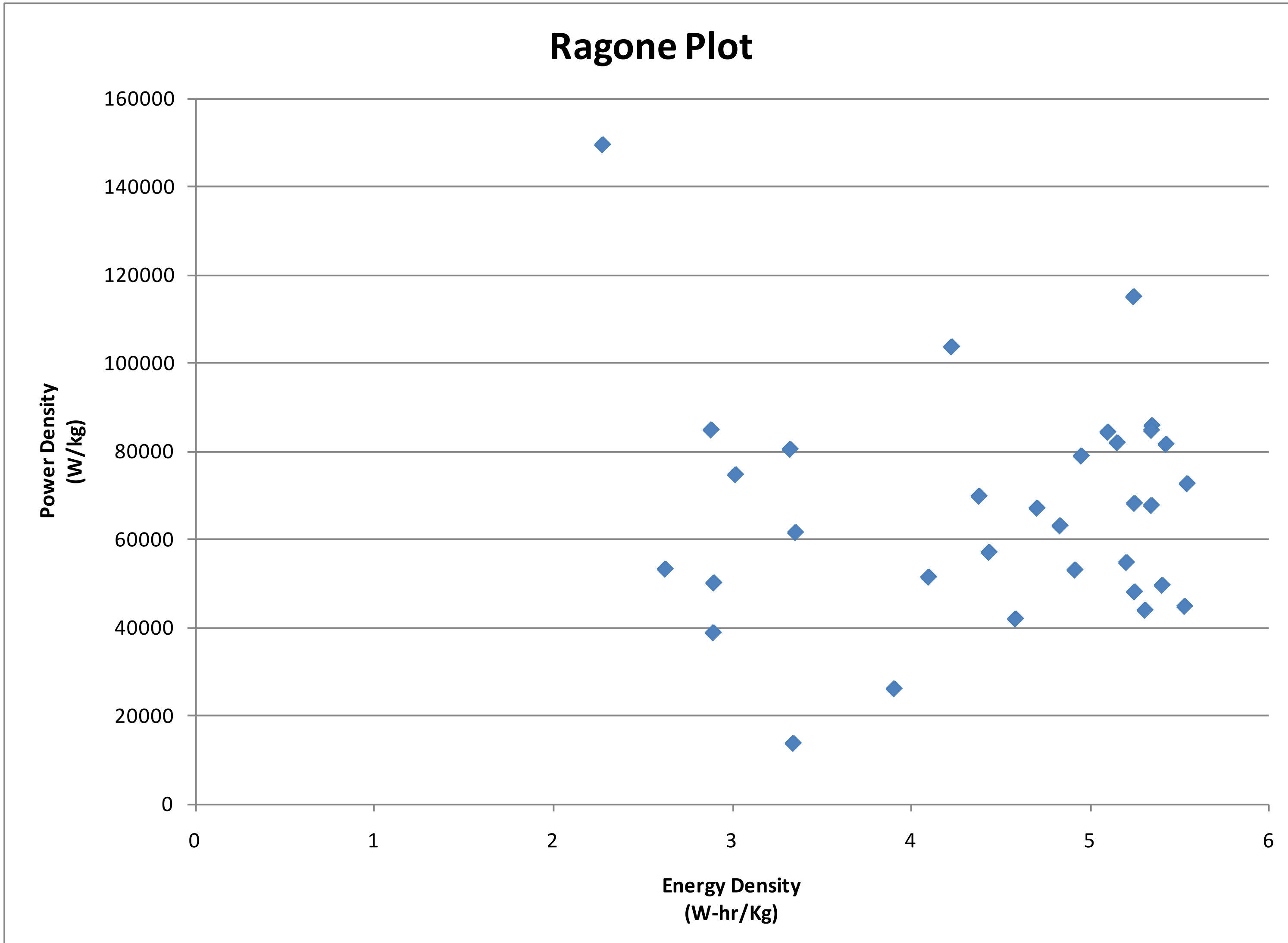
Model 1260A Impedance / Gain-Phase Analyzer & 1287 Electrochemical Interface

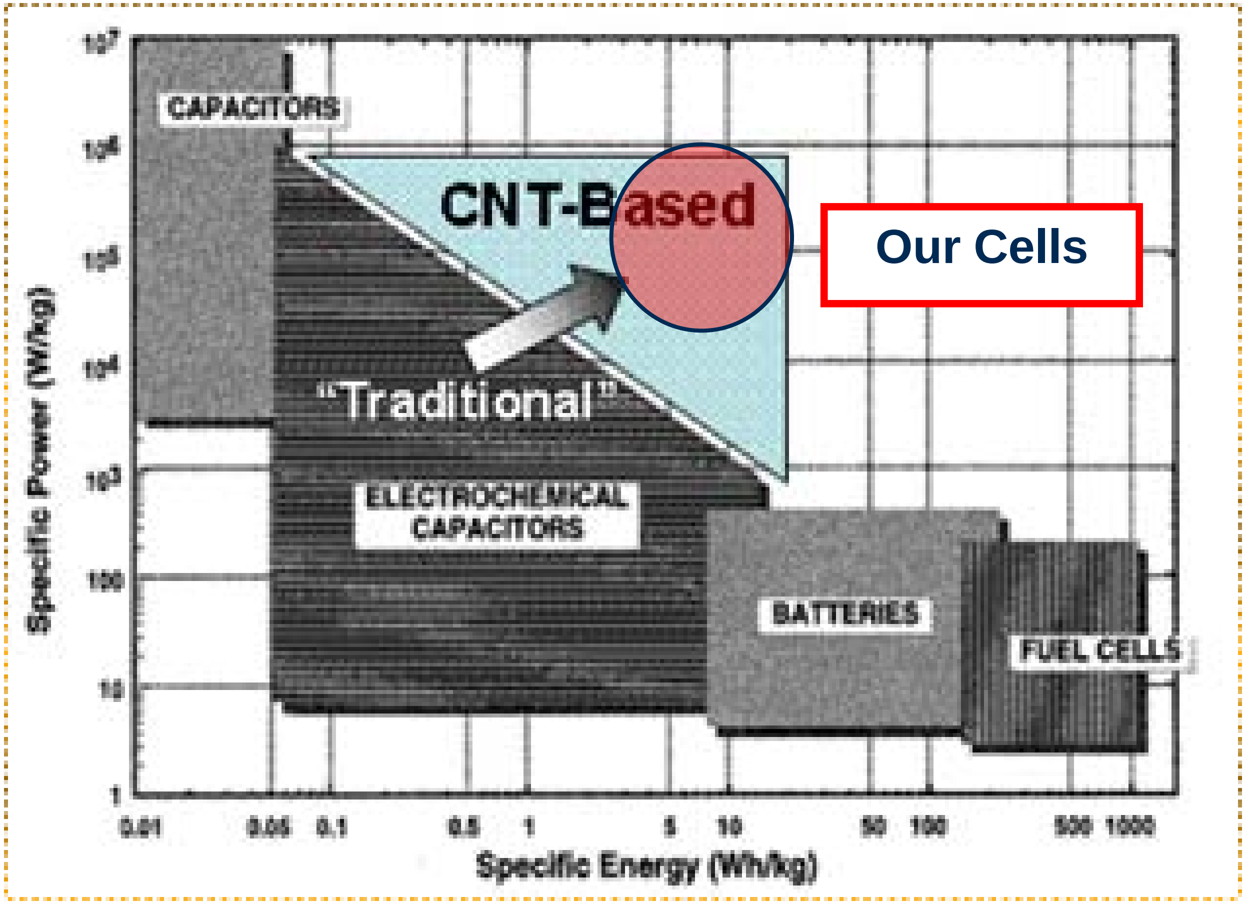
(Government Furnished Equipment by AMRDEC)

- Charge/Discharge
  - Apply constant current to measure max voltage in cell. Open circuit testing indirect measures capacitance via remaining charge.
- Impedance Spectroscopy
  - Apply variable frequency current and measure impedance of system due to resistive and capacitative elements in cell.
- Cyclic Voltammetry
  - Apply voltage sweep across discrete voltage window and measure the current between the working and counter electrode.

Status of Technology

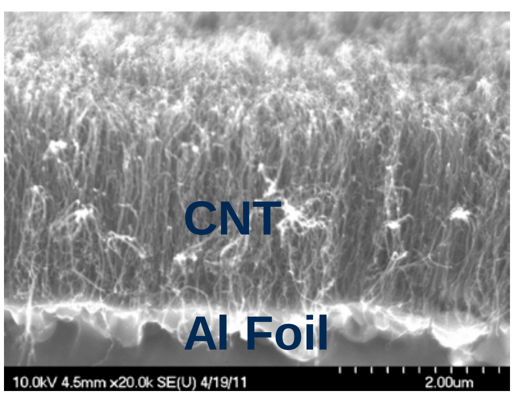


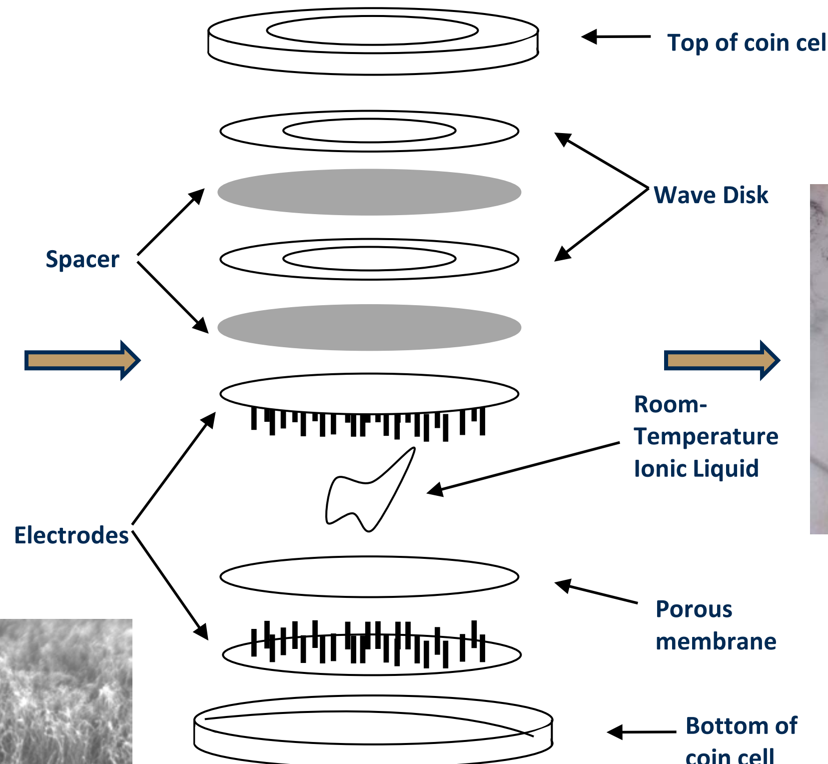

Ragone Plot
Power Density (W/kg)
160000
140000
120000
100000
80000
60000
40000
20000
0
0
1
2
3
4
5
6
Energy Density (W-hr/Kg)


CAPACITORS
CNT-Based
Our Cells
"Traditional"
ELECTROCHEMICAL CAPACITORS
BATTERIES
FUEL CELLS
Specific Power (W/kg)
Specific Energy (Wh/kg)
0.01
0.05
0.1
0.5
1
5
10
50
100
500
1000

Supercapacitor Assembly

Materials





Finished Cell

Future Research Directions

- Pseudocapacitive Functionalization
- Active electrodes with anisotropic porosity
- Aligned growth on foils
- Electrolyte modifications

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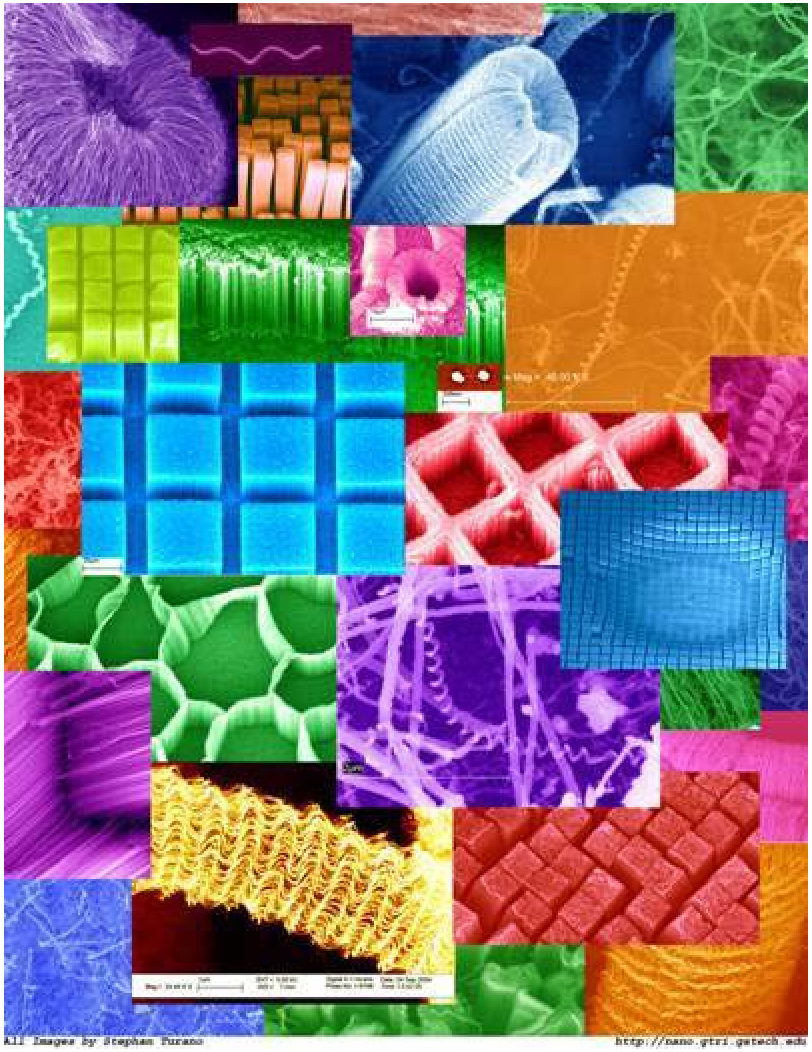
Q/A?



All Images by Stephan Turano http://nano.gtri.gatech.edu

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